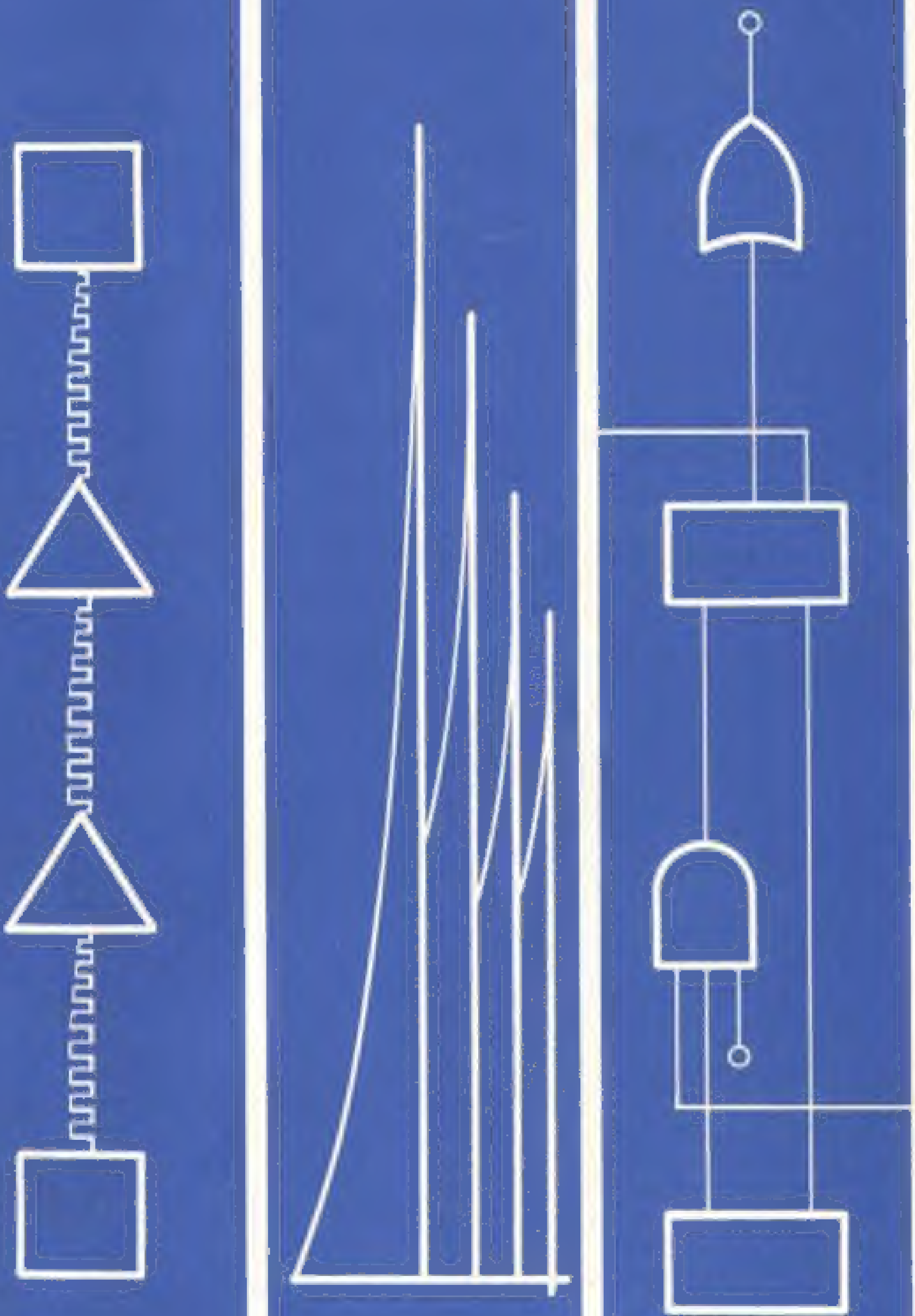

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COVER -Artist's interpretation of:
Pulse Code Modulation
Cost Effectiveness
D1 Channels

Pulse Code Modulation—Initial Application at Western Union

C. C. Batterson, R. G. De Witt, and F. J. Parra

PCM was invented in 1938 by A. H. Reeves who was associated with ITT in Europe. Some important ideas are conceived before the practical means to implement them are available. Many of Charles Babbage's ideas (1792-1871) which were the beginnings of the modern computer could not be practically implemented during his lifetime due to a lack of adequate materials and components.[1] PCM represents another example of this since the invention of the transistor in 1948 was required before PCM became practical for common carrier communications. PCM and computers have much in common. They both manipulate information which is coded in binary digital form. Therefore, they both make use of high-speed switching transistors which are now being replaced by integrated circuits with a savings in cost and space. Large scale integration (LSI) may bring another reduction in cost and size to both. Since PCM and computers are alike in many respects it is not surprising that they are easily married to create ideal computer data networks with low cost, high performance, low maintenance and high reliability.[2]

A classic paper by B. M. Oliver, J. R. Pierce and C. E. Shannon in 1948 acted as a catalyst to spur development work in PCM.[3] Full production of the first common carrier PCM system, the T1 Carrier, was started by the Bell System in 1962 and the rapidity of its deployment in the Bell plant has been phenomenal.[4, 5, 6, 7]

The T1 Carrier System provides 24 voice bands suitable for high speed data transmission without additional channel conditioning. The T1 is a full duplex system requiring a send cable pair and a receive cable pair both of which have been conditioned with regenerative repeaters incrementally spaced over the entire cable run and remotely powered from a central office via a dc simplex circuit. The T1 Carrier terminal transmits a 1.544 megabit bipolar pulse train to the line.

A version of this pioneer PCM system was manufactured by VICOM. This design called, VICOM T, reduced the T1 type PCM Terminal size by a factor of 3 through the liberal use of integrated circuits. In 1967 when Western Union decided to enter into PCM operation by engineering and installing a trial system, it used this type PCM equipment, which was then available off the shelf, to meet its planned installation schedule.

Standard Voice Channel PCM

Figure 1 is a block diagram illustrating the various operations performed in a Standard Voice Channel PCM System. First the voice channel must be sampled. According to the Nyquist sampling theorem, if samples are taken at a rate equal to at least twice the highest frequency in the sampled band, no information will be lost and therefore the signal can be reconstructed with no error at the receiver. Verification of the sampling theorem can be seen in Figure 2b since the adjacent copies of the original spectrum just touch at the Nyquist sampling rate. The dotted line, an ideal low pass filter characteristic, shows that at this sampling rate or higher, the original spectrum can be recovered without distortion. However, if the sampling rate is lower, then adjacent copies of the spectrum will overlap and recovery of the original spectrum without distortion will be impossible.

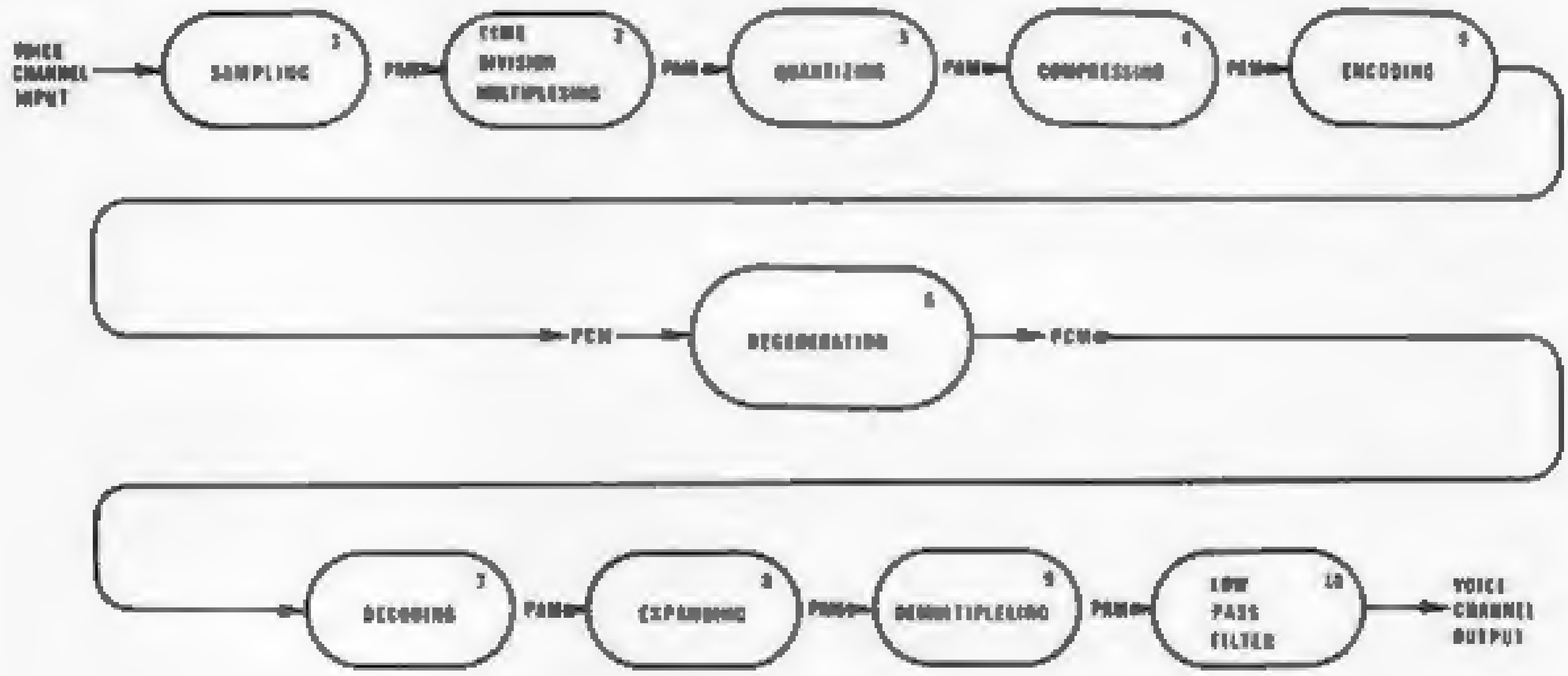


Figure 1—Functional Block Diagram of a PCM system

a) Sampling

The sampling operation, the first operation in Figure 1, can be thought of as a modulation process, with a train of impulses acting as the carrier and being product modulated by the signal.[8, 9] A product of functions in the time domain results in a convolution of the respective spectra in the frequency domain. The convolution can be made graphically and results in the spectrum shown in Figure 2b with the original voice signal spectrum shown in Figure 2a. Hence, the process of sampling causes the spectrum of the original analog signal to be repeated periodically, centered at multiples of the sampling frequency. In Figure 2b the sampling rate is exactly twice the highest frequency in the voice signal spectrum. Verification of the sampling theorem can be seen in Figure 2b since the adjacent copies of the original spectrum just touch at the Nyquist sampling rate.

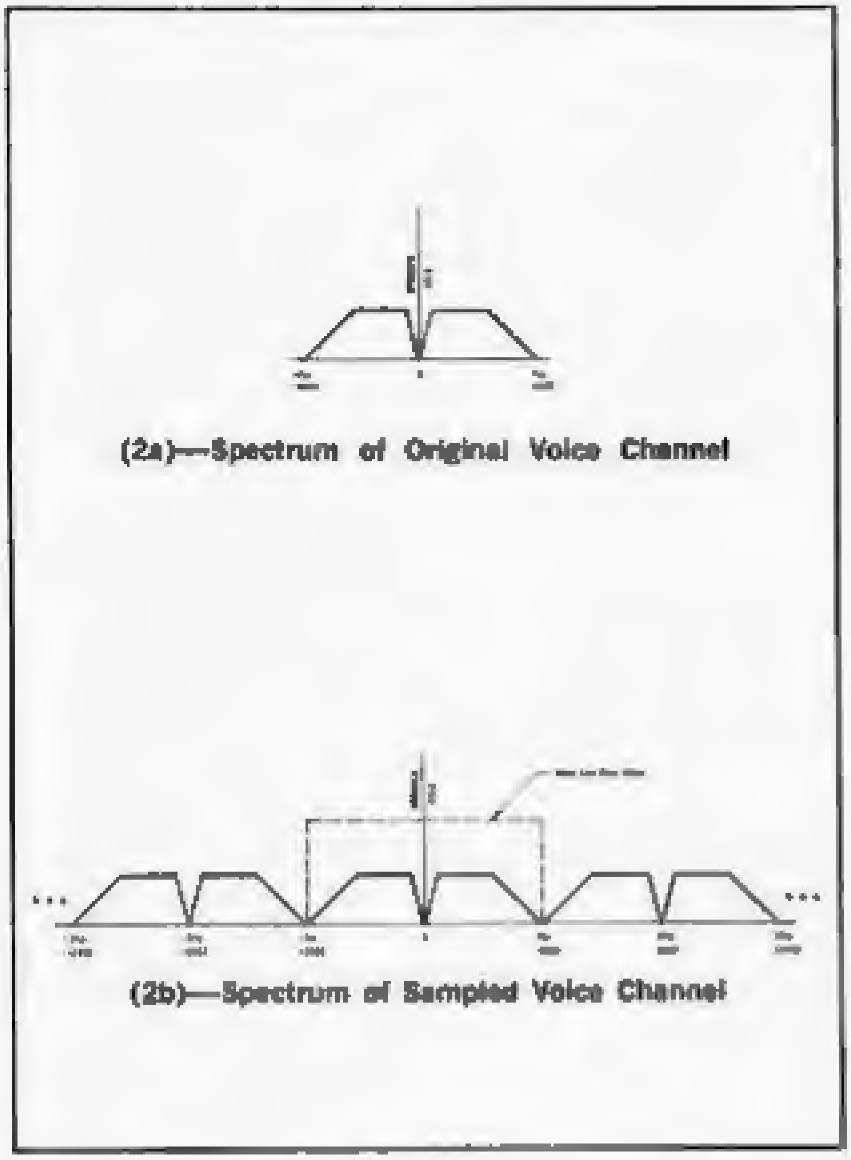
b) TDM

When samples from many different channels can be interleaved in the space between samples of one channel, it is called Time Division Multiplexing, the second operation in Figure 1.

c) Quantizing

In order to make use of digital transmission with regeneration (which is the payoff since it makes possible transmission over any distance with negligible errors and distortion), the narrow PAM (pulse amplitude modulated) samples must be quantized, as accomplished in the third operation in Figure 1.

This rounding off of samples causes a small distortion called quantization noise, which can be made as small as desired by design.



(2a)—Spectrum of Original Voice Channel

(2b)—Spectrum of Sampled Voice Channel

Figure 2—Comparison of Spectrums of Original and Sampled Voice Channel

d) Compressing

The next operation in Figure 1 called compressing, is needed to improve the signal-to-noise ratio of the low-level signals. This is accomplished by amplifying them more than the high level signals (non-linear amplification), so that the low-level signals will overlap more encoder steps.

e) Encoding

The rounded off samples can now be converted to binary codes in a coder, the fifth operation, since there are only a discrete number of amplitudes as a result of quantization. For example a seven bit binary code can represent 128 (2^7) discrete amplitude levels.

f) Regenerating

Now the binary codes can be sent over the digital transmission line with regenerators, the sixth operation, located as often as needed or they can be converted to some form of multi-level signal prior to transmission over a line with appropriate multi-level regenerators. Figure 3 shows the time sequence in the movement of one particular pulse (pulse A) from the PCM transmitter to the PCM receiver in order to describe the most important function in a PCM system, regeneration. Pulse A leaves the PCM transmitter as a clean square pulse at t_1. Half way to the first regenerator, at t_2, it has been rounded and spread due to the frequency limitations of the media and it has some interference riding on it. When it reaches the first regenerator, at t_3, it has been rounded and spread some more and has even more accumulated interference riding on it. The regenerator is so placed by design that it is reached before the interference can accumulate sufficiently to cause more than a negligible number of decision errors. Therefore, the first regenerator produces an exact replica of the original pulse A. The same process is repeated for each additional regenerator section, until the office regenerator is reached and an exact replica of the original pulse A is fed to the PCM receiver.

g) Decoding

At the receiver there is a translation back to binary, if it is needed. Then each binary code is decoded back to PAM samples, the seventh operation, in Figure 1.

h) Expanding

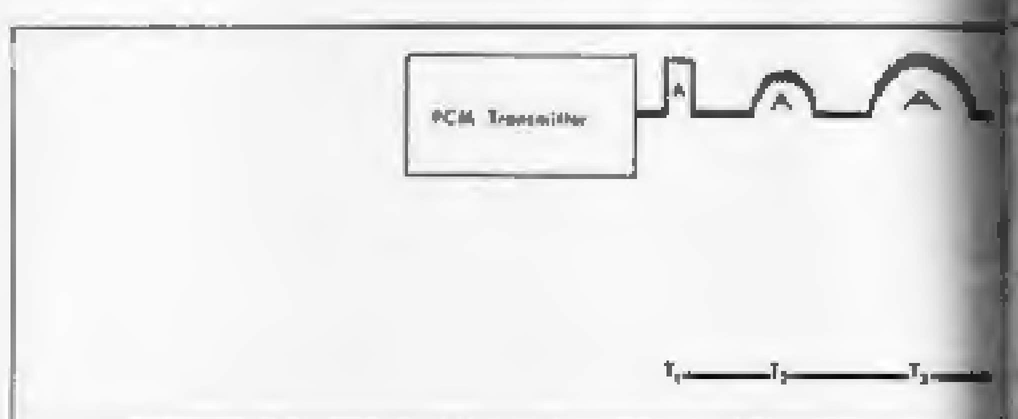
The samples are non-linearly expanded in the eighth operation, expanding to remove the effect of the compressor and make the compander (compressor and expander) linear over-all.

i) Demultiplexing

Each PAM sample is then distributed to its corresponding voice channel, this is called demultiplexing, the ninth operation in Figure 1.

j) Low Pass Filter

Finally, a simple low pass filter can be used in the last operation to extract the original signal from the PAM samples.



First PCM Installation at Western Union

Before starting a digital network in Western Union's plant several factors had to be evaluated by installing a trial system. The first was to evaluate the cable plant for digital operation. The second was to evaluate the available PCM equipment with respect to reliability and performance. The third was to evaluate the impact of PCM systems on operations and maintenance personnel.

With regard to the first factor, several questions needed to be answered. The first question was whether or not PCM would be feasible in Western Union cables because of their age, the presence of a large amount of 13 and 16 gauge pairs, and the frequent insertion of pieces of new 19 gauge cable to replace failed sections of the 13 and 16 gauge cable. Another question was the effect on PCM of the many 120 volt ground return d.c. telegraph circuits which would be in the same cables with PCM signals. Finally, an answer was needed as to whether or not the impulse noise emanating from a Western Union switching center was sufficient to require a shortening of the first repeater span out of the office.

It will be shown later that any reservations that might have existed with regard to these three factors were completely dispelled by the excellent performance of the PCM equipment in the Western Union Cable Plant environment and the enthusiastic reception of this equipment by the operations and maintenance personnel.

Engineering the Route

In order to evaluate the above factors, first the route had to be engineered with regard to a number of considerations. These were:

1. Near-end crosstalk data
2. Location of repeaters
3. Loss of pairs
4. Impulse noise
5. Discontinuities

a) Near-end crosstalk data

Since for one cable operation of PCM the primary limiting factor is near-end cross-talk, the first need was to get the maximum separation between the two directions in the cable.[5] Most of the cables encountered along the route between New York and Newark contained only 13 and 16 gauge cable pairs with the two different gauges located in different layers. Hence, the only opportunity for separation of the two directions was to use 16 gauge pairs to transmit from East to West and 13 gauge pairs to transmit from West to East. The cross-talk effect of the existing 19 gauge replacement sections was disregarded as nothing could be readily done to improve the separation in these randomly spliced cable sections. Fortunately, these sections were short and contributed little to the overall cross-talk. In future cable replacements and installations, care must be taken to preserve the layer or unit integrity of the cable to minimize the adverse effect of cross-talk.

The design loss of a T1 repeatered section is approximately 30 db at 772 KHZ. Assuming a ten section repeatered line, an objective error rate of 10^{-7} per repeater would be sufficient, in the worst case, to yield an overall end-to-end objective error rate of 10^{-6}, which is the minimum acceptable for a T1 carrier line. To attain this, an RMS signal-to-noise ratio of 17 db or greater must be present at the input to each repeater. Adding the design loss of 30 and signal to ratio of 17 gives 47 db for the near-end cross-talk requirement of a single system. Here, it was assumed that the cross-talk is similar to gaussian noise in character—a very common assumption in engineering studies.

With the assumption of gaussian noise, the effect of the independent interferers follows a power law. Western Union traffic consists of many low

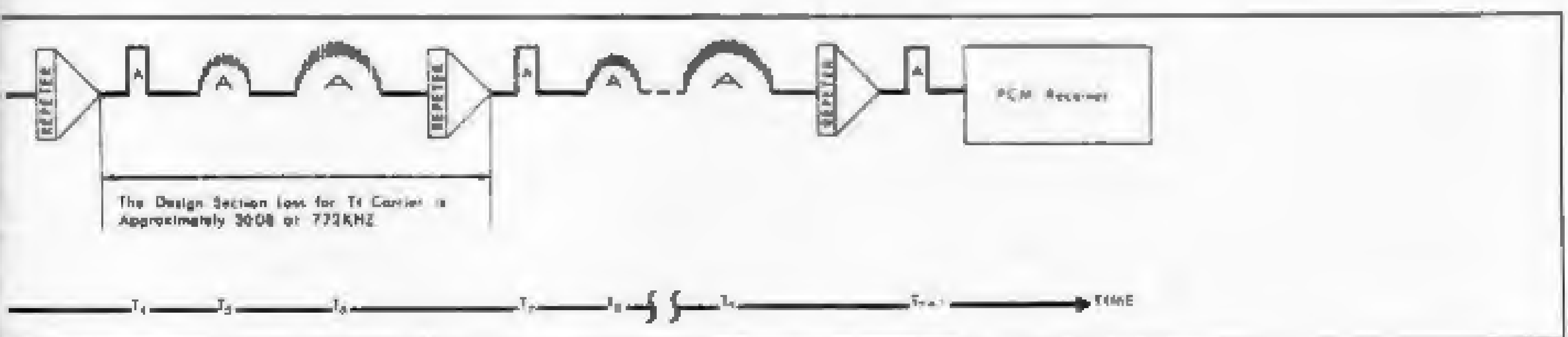


Figure 3—Life History of Pulse A

density routes. Therefore, no route is expected to grow beyond 10 systems over the next ten years. The objective error rate of 10^{-6} must be met for each of the 10 operating systems. Consequently, adding 10 db to the 47 db requirement for a single interferer, the final near-end cross-talk requirement becomes 57 db, as measured in a worst case test in which the frequency from 400 KHZ to 1.2 MHZ is swept.

Table I lists some measurements of near-end cross-talk for a typical cable and Figure 4 is a plot of the near-end cross-talk as a function of frequency for a typical Near End Cross-talk path for the same cable. The above criteria is sufficient to guarantee satisfactory operation of 10 T Systems in the same cable; empirical data is being collected to determine if it is also necessary. This data may justify a reduction in the criteria.

TABLE 1

No. Transmitting Pr ↓ (13 ga) / No. of Receiving Pr → (16 ga)		129-130	139-140	149-150	159-160	169-170
3-4	76db 450kHz	75 1000	76 450	74 590	67 780	73 425
9-10	76db 870kHz	71 400	73 440	73 720	68 440	71 620
21-22	73db 400kHz	76 405	76 430	73 420	77 890	71 400
27-28	75db 450kHz	71 1000	73 830	70 440	66 450	72 415
15-16	73db 990kHz	76 740	78 445	75 1000	77 930	68 450
33-34	69db 445kHz	67 450	73 445	71 980	72 430	69 445

Shows Worst Case NEAR-END CROSS TALK (NEXT) LOSS MEASUREMENTS Over the frequency range 0.4 to 1.2 Megahertz taken on Western Union 18 CABLE at New York with a 100 ohm Termination at Erie Cable House.

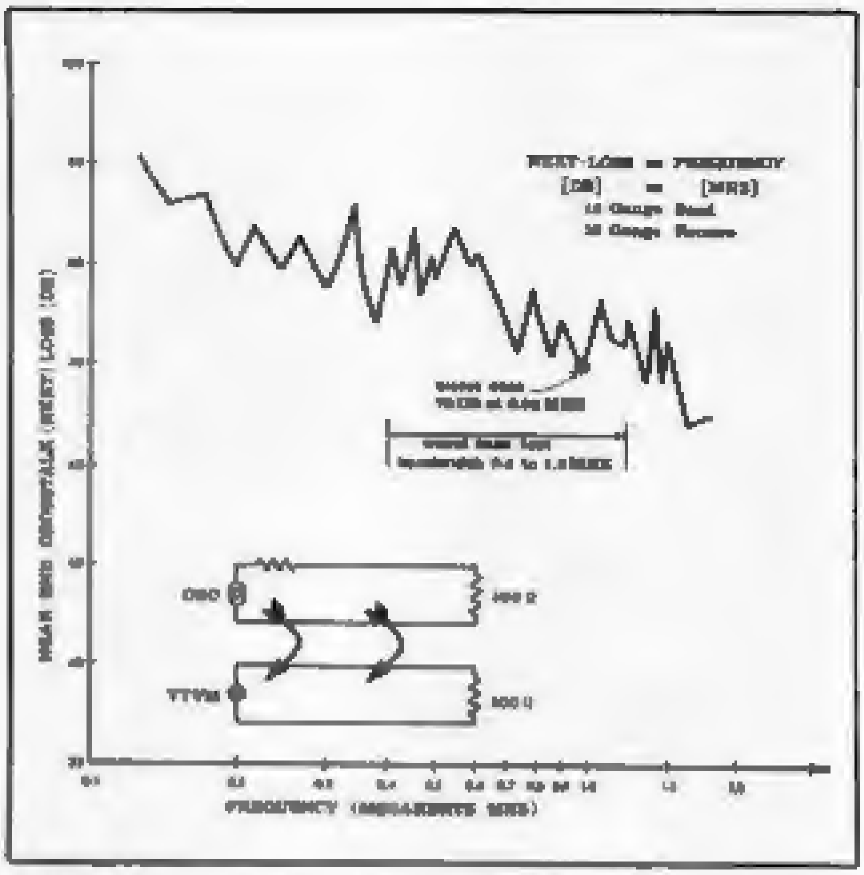


Figure 4—Plot of Near-End Crosstalk Loss vs. Frequency

b) Location of Repeaters

The next practical consideration was to determine where to locate repeaters. The WU cable chosen for the service trial between New York and Newark runs along the Erie-Lackawanna Railroad most of the way where a number of cable huts were available. These became prime locations for repeaters because of the ease with which repeater cabinets could be installed and maintained.

c) Decibel Loss

Fortunately, these locations also were at convenient distances in terms of the attenuation of 13 and 16 gauge cable pairs. At 772 KHZ, this would be about 10 db per mile or at least 3 miles for a maximum section of 13 gauge and about 13 db per mile or at least 2.4 miles for 16 gauge.

For the selected T1 route shown in Figure 5, the first cable house (Erie C.H.) was within full section range (30 db) on both gauges of pairs.

d) Impulse Noise

There was some question as to whether the impulse noise from 60 Hudson Street would be sufficient in amplitude, frequency of occurrence and character to prevent the use of a full section. An initial experiment proved the full section was satisfactory and it has since proven satisfactory in the service trial.

The results of tests run on an EM4 Channel Unit showed virtually no measurable impulse noise; whereas a typical FDM channel over a similar route does contain a significant amount of noise.

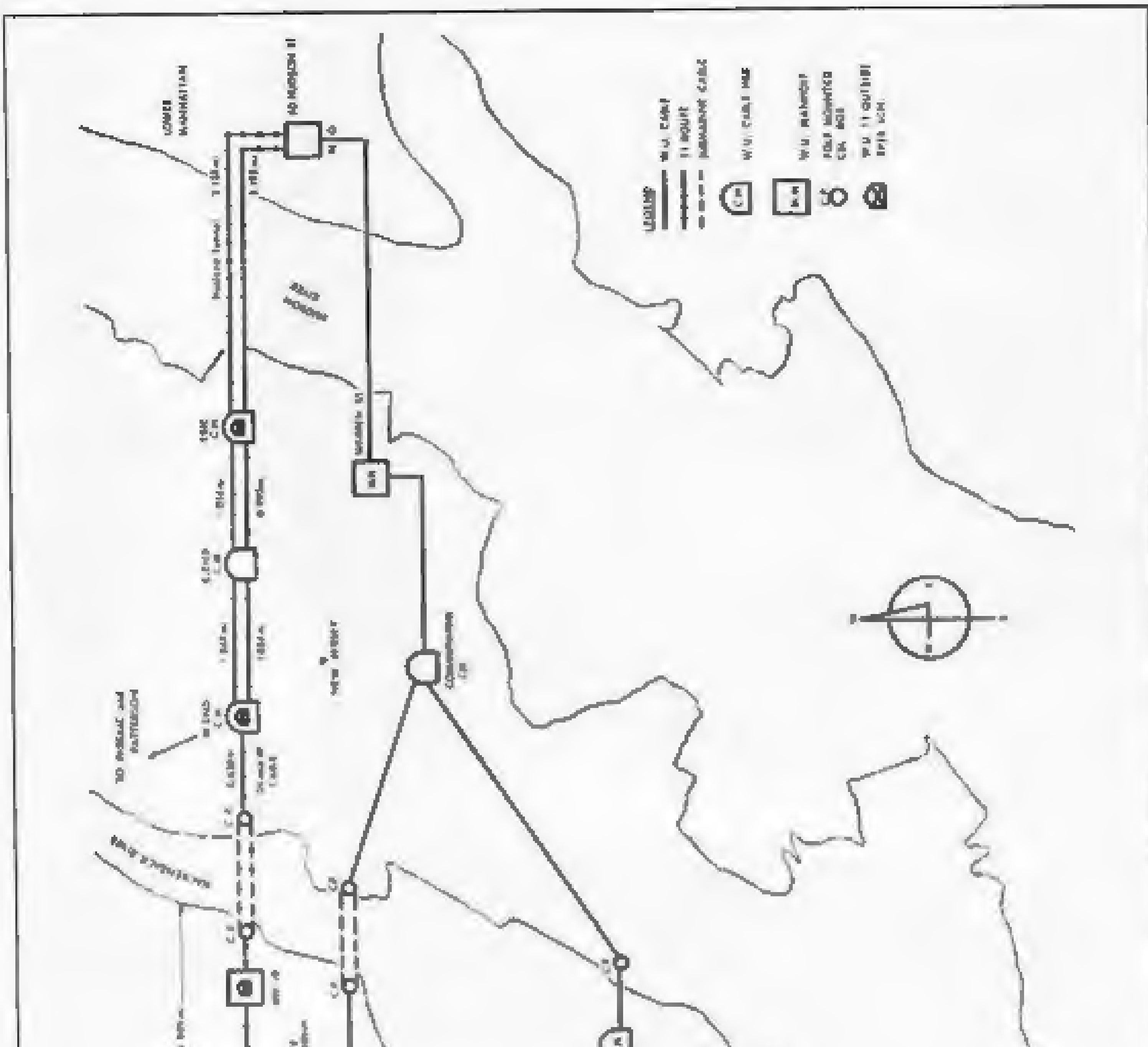


Figure 5—Western Union's Cable Routes between New York and Newark

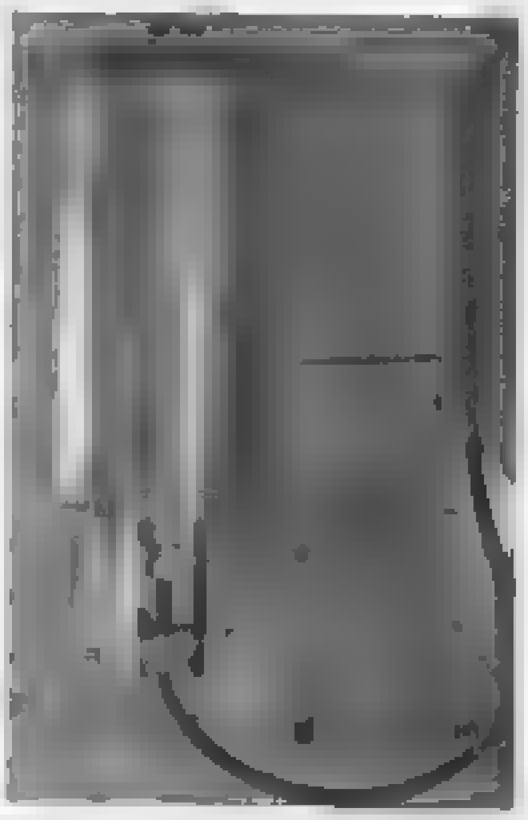


Figure 6—A Typical Repeater Installation

(a) cover on

(b) cover removed

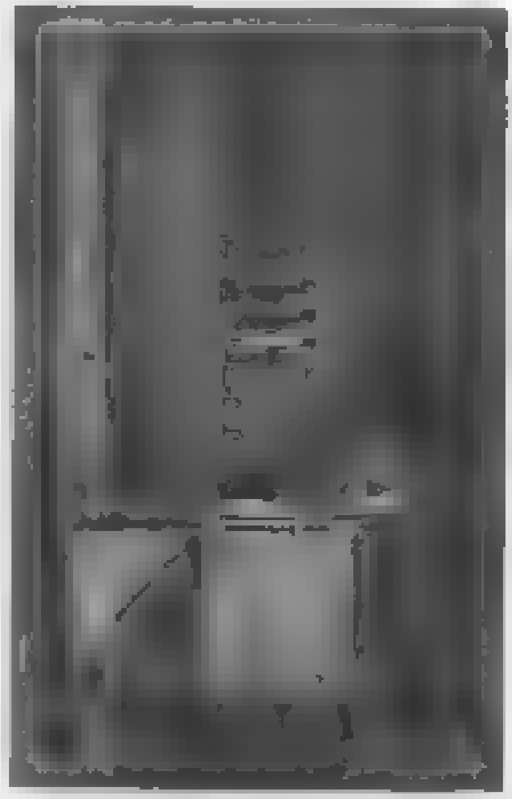


Figure 6a shows the installation of the repeater cabinet at the Erie Cable House with the cover on. Figure 6b shows the same cabinet with the cover removed showing three plug-in regenerators, nine more may be added. The East End Cable House is about one mile from the Erie Cable House and the West End Cable House is about one mile farther towards Newark. Due to many repairs with pieces of 19 gauge cable it was not possible to transmit all the way from Erie to West End on the 16 gauge pairs due to excessive attenuation. At the same time, it was felt that a repeater at East End would be wasteful. A compromise solution was arrived at which involved cross-connecting pairs. The 16 gauge pairs were used to transmit from Erie Cable House to East End and then crossconnected to the 13 gauge pairs to continue to West End. West End transmits toward Erie Cable House on 16 gauge pairs and then these are crossconnected at East End to 13 gauge pairs to get from there to Erie Cable House. The net result was a section loss of about 28 db in both directions. If more pieces of 19 gauge cable are added at a later date, anywhere between Erie and West End another repeater can be easily installed at East End. Beyond West End, the Jersey Meadows are encountered and there is no cable hut available until the Erie Lackawanna Railroad Station in Newark is reached some 6 miles away. With no alternative to using manholes, the distance was simply split equally into three two-mile hops to accommodate both gauges of cable pairs. As a result repeaters were located at Manhole MH 19 and Manhole MH 37, shown in Figure 6. Figures 7a and 7b show a different type of installation underground rather than in a cable house. Figure 7a shows the repeater cabinet as installed in Manhole 37 and Figure 7b shows the same cabinet with the cover removed so that the plug-in repeaters can be seen.

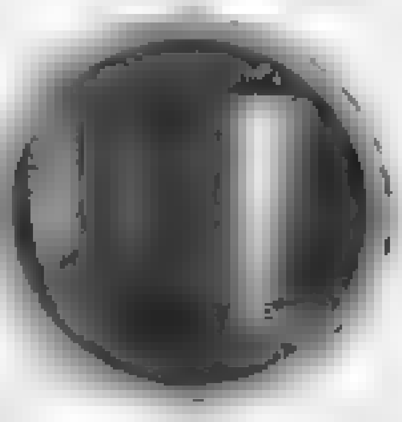
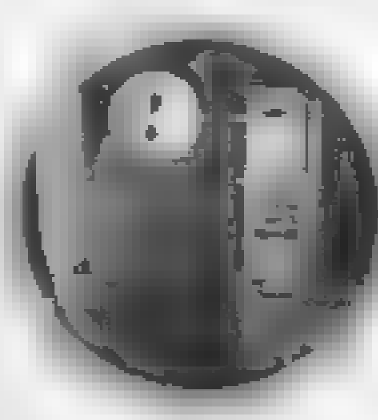


Figure 7—A Repeater Installation in a Manhole

(a) cover on

(b) cover removed



From the Erie Lackawanna Station in Newark, it was a short hop of about one mile into the new WU Newark Office with 16 and 19 gauge cable pairs available

e) Discontinuities

Another practical consideration is the large number of discontinuities. These are points where a pair being used changes from one gauge to another not co-terminus with repeaters. As in any high frequency transmission facility, be it a wave guide coaxial cable or a cable pair, discontinuities cause reflections of pulses. These reflections, if they are of sufficient amplitude, can interfere with the proper operation of the regenerator and cause errors.[4] The degrading effect of the reflections is easily cured by adding balanced "O" pads of from 3 to 6 db between the regenerator output and the transmit pair wherever the cable records show that a discontinuity is within 9 db of the regenerator output. If the cable records are not up to date, the presence of troublesome reflections can be detected by the VICOM Span and Repeater Test Set shown in Figure 8. An appropriate pad can then be inserted after the magnitude of the reflections has been ascertained by using a portable oscilloscope such as the Tektronix 422

Initial Traffic Put on the System

Figure 8 shows the service trial installation of the T Terminal Shelf, Span Terminating Shelf and test equipment in the New York office

A 4 Wire E&M channel unit is adequate for most Western Union requirements for voice channels. The one exception is for Hot Line and PATS (Private Automatic Telephone System) customers who are close enough to the Subscriber End PCM Terminal to make use of a Foreign Exchange type Channel Unit which was specially designed and manufactured for Western Union by VICOM, according to Western Union specifications

For the first six months of the service trial the traffic on the system consisted of two Type 70 Class "D" (150 Baud) Frequency Division Multiplex (FDM) Carrier Groups. Also a 2400 baud data test signal produced by a pseudo-random word generator, driving a Western Electric 201B modem was used for monitoring voice channel error rate. This was used for comparison with the line error rate as measured by a bipolar constraint violation detector. Each of these three signals utilizes a pair of 4W E&M Channel Units. In addition four PATS circuits each utilizing a pair of the special FX type Channel Units which consists of a Switch End Channel Unit (FX-UPC) and a Subscriber End Channel Unit (FX SUB) have been in service

The FX SUB Channel Unit provides basically the same functions as the standard Dial Pulse Originating Channel Unit, with the added capability for ringing the subscriber's sub set; and the FX UPC Channel Unit provides basically the same functions as the Dial Pulse Terminating Channel Unit with added capability to recognize ringing from a switch and transmit this information in a coded form to the FX SUB Channel Unit

In the near future six more voice bands of traffic will be added to the system. These voice bands will carry data at various speeds.

Tests were made on a trial system carrying traffic which was representative of different kinds of Western Union services. These tests provided information regarding operations and maintenance as well as performance and reliability

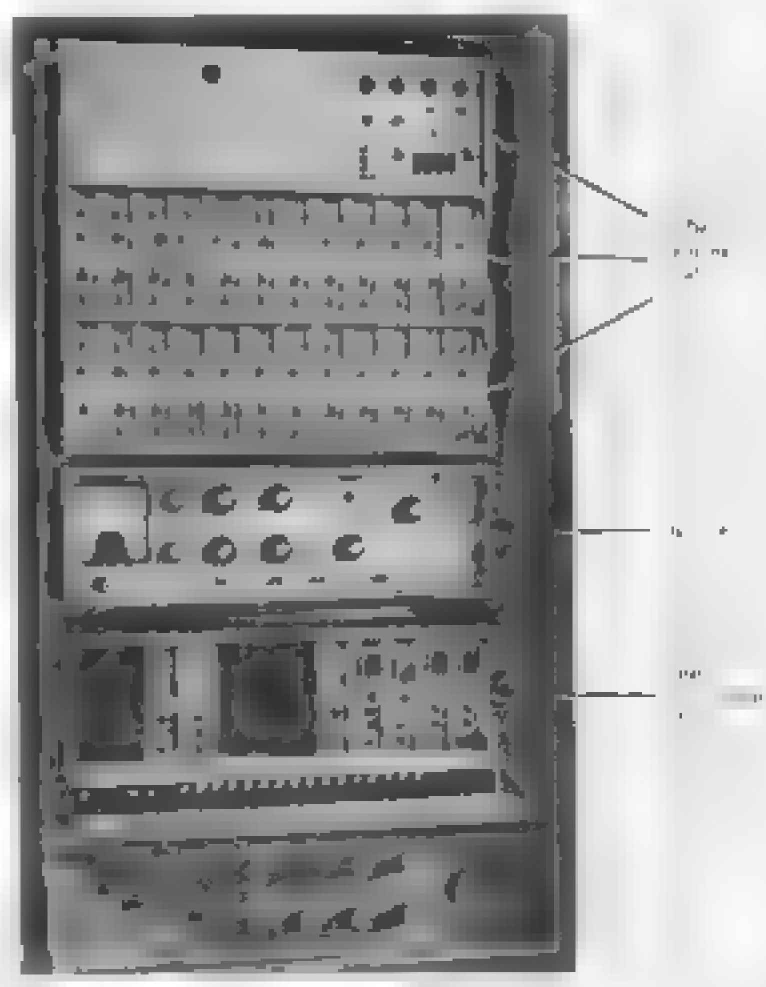


Fig. 8—PCM Terminal used in Service Trial in New York. The VICOM span and Repeater Test set is shown on the Terminal Rack

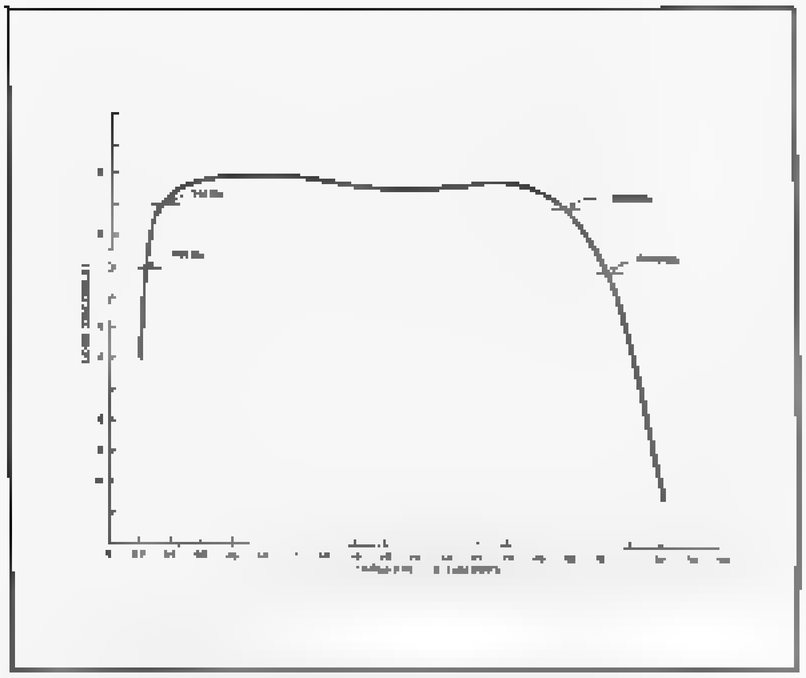


Figure 9—Plot of Attention Loss vs. Frequency for a PCM Voice Channel

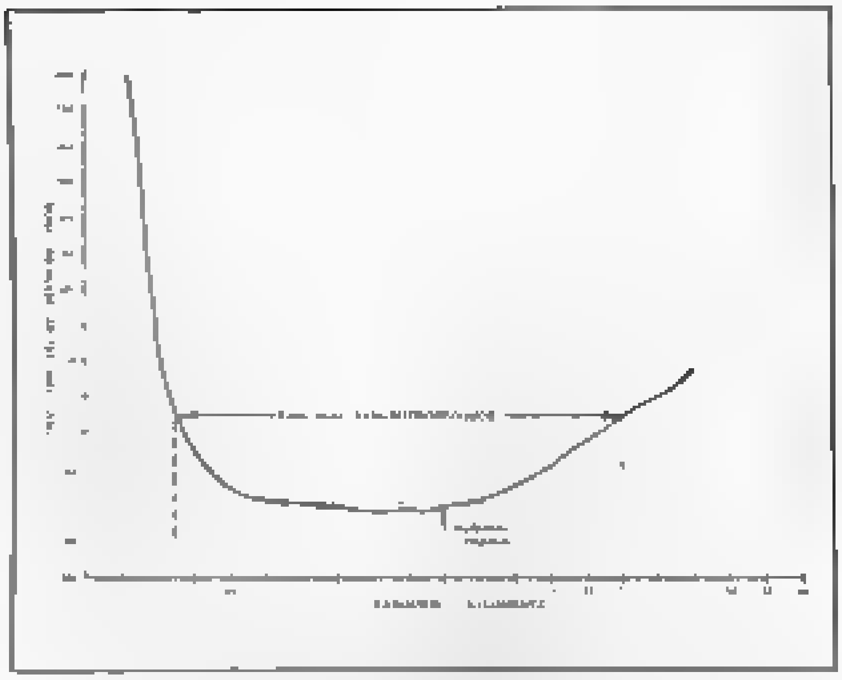


Figure 10—Plot of Envelope Delay vs. Frequency for a PCM Voice Channel

Performance and Reliability

During the first six months in service the system was monitored with respect to its performance and reliability. The results were excellent. There were no service interruptions due to PCM equipment failure.

For a T1 type repeatered line, error rate is the only significant measure of performance. The error rate of the repeatered line in service, averaged less than one error in 10^8 bits. This line error rate was measured directly using a bipolar constraint violation detector. It was also checked indirectly by using a pseudo-random 2400 bit per second data generator and Western Electric 201B modem to transmit over one of the twenty-four voice channels. The voice band data was checked bit by bit for errors and a sequential record of errors was printed out. The error data was examined with respect to two hypotheses. First the error rate was found to be low despite a full section out of the 60 Hudson Street office. Hence, there was no significant impulse noise contribution to the error rate. Second, the error rate was low despite the presence of many 120-volt ground return D.C. telegraph circuits in the same cable. Thus the null hypotheses must be accepted in both cases.

The most important parameters of a PCM voice channel are amplitude and envelope delay as a function of frequency, idle channel noise, impulse noise, and interchannel crosstalk. Once these parameters have been measured, the limitations (for example the number of sections in tandem) and the corrective adjustments (for example delay equalization) that must be imposed to meet Western Union criteria for various voice, data, and facsimile services can be determined.

The amplitude and envelope delay characteristics are a function of the send and receive low pass filters, while noise is a function of both the line and terminal performance. An EM4 Channel Unit was selected for these tests because it will be used for Western Union Service Offerings requiring the strictist criteria.

The envelope delay of this 4-wire channel unit is less than 300 microseconds between 500 and 3000 Hz and the amplitude response is down 1 db at 313 and 2950 Hz and down 3 db at 243 and 3205 Hz. Fig. 9 and Fig. 10 show the Amplitude and Envelope Delay Response of the EM4 Channel Unit respectively. This unequalized voice channel will meet all Western Union's Amplitude and Envelope Delay Criteria with only two exceptions. When used as a NASA 600B switched circuit or a Broadband trunk circuit, slight conditioning will be required. A new channel unit has since been developed which extends the upper 3 db point to 3400 Hz. This may have a better envelope delay characteristic.

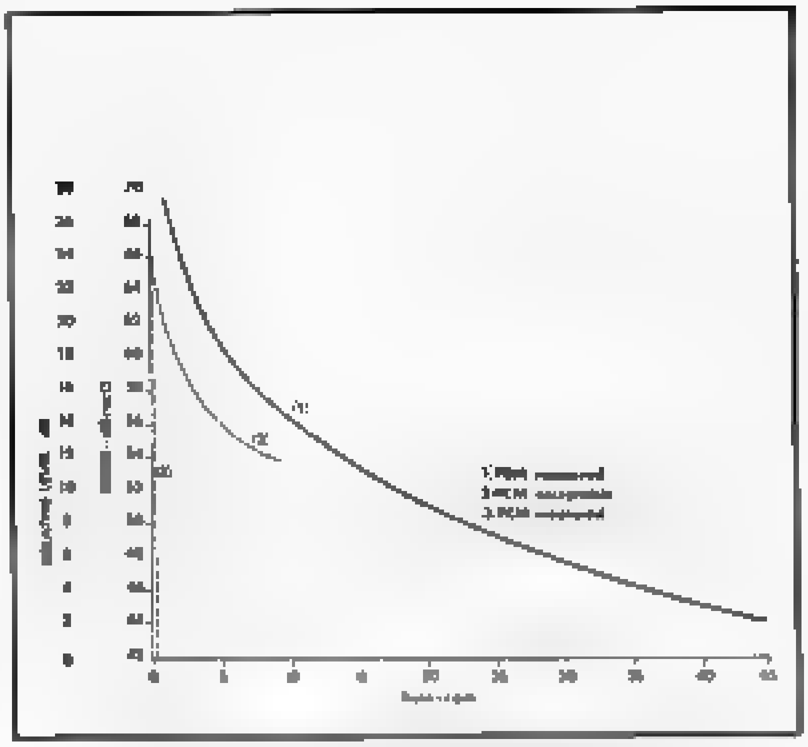


Figure 11—Comparison of Impulse Noise in FDM and PCM Channels

Tests were also run to determine if this channel unit would provide adequate low noise performance.

The criteria accepted throughout the industry for a T1 type channel are listed below:

1. Idle channel noise		28 dBrncO
2. Impulse noise	a)	20 counts maximum in 5 minutes over 58 dBrncO
	b)	1 count maximum in 5 minutes over 64 dBrncO
3. Interchannel crosstalk		35 dBrncO

The results of these tests run on an EM4 Channel Unit were:

1. Idle channel noise		(worst case channel) 20 dBrncO
2 Impulse noise	a)	O counts (worst case channel) in 5 minutes over 58 dBrncO
	b)	O counts (worst case channel) in 5 minutes over 64 dBrncO
3 Interchannel crosstalk		(worst case channel) 33 dBrncO

Figure 11 shows 3 curves representing the measured and acceptable level of impulse noise on FDM and PCM channels. Curve (1) is the results of tests of impulse noise amplitude distribution measured on an FDM chanel. Curve (2) is the impulse noise on a PCM channel which is acceptable to the communications industry, and (3) is the impulse noise measured in Western Union's trial system, on a PCM system. Since the tests showed that PCM voice channels are of superior quality, Western Union plans to use them in providing many different services.

The test data shows that PCM voice channels are of superior quality and Western Union plans to use them to provide many different services.

Note that a T1 type PCM voice channel has an impulse noise requirement which is superior to the typical FDM voice channel. This was discussed in the article entitled, "Measurement and Analysis of Impulse Noise for Communications Circuits" which appeared in the Spring 1968 issue of the Western Union TECHNICAL REVIEW. Furthermore, the actual impulse noise measured on the PCM voice channel is significantly below the requirement. It can readily be seen that an all PCM digital network would have the capability to significantly reduce impulse noise at the customer interface with the communication network.

The PCM system acts like a buffer to prevent the impulse noise from reaching the customer. This is a consequence of regeneration. Regenerative repeaters prevent all interference including impulse noise from propagating to the customer interface. It is analogous to the pony express in which each rider passed the mail to another rider before his horse got too tired and susceptible to errors. Hence, the probability that a given pouch of mail would get through without error was significantly increased.

In order to provide added reliability for the system with the traffic load increasing substantially, three additional steps have been taken. First, a backup T1 repeatered line which traverses a physically diverse route was obtained.

Second, a remote control line switching unit was designed, installed and tested. When a key is turned at 60 Hudson Street the terminals at both ends are transferred from the primary line to the backup line. This latter feature is needed because only 60 Hudson Street is manned 24 hours a day.

Last but not least a second training course has been scheduled in order to train more men so that T trained men will be available at all times.

Potential of PCM

Because PCM provides essentially errorless and distortionless transmission independent of distance, the growth of PCM networks has been rapid in the United Kingdom, France and Japan as well as the United States. This initial growth has been in the area of short haul facilities, from 2 to 200 miles. It is very likely that this growth will accelerate when long haul PCM becomes available to provide coast to coast PCM channels. The impact of PCM integrated transmission and switching will further accelerate PCM network growth[10, 11, 12, 13, 14, 15, 16]

At Western Union, development work is under way on PCM terminals which will provide direct digital data channels for 200 baud and below, suitable for telegraph and data and direct digital channels for 2400, 4800 and 50,000 bit per second. All of these are classified as D^4 (Derived Direct Digital Data) channels and are described in the article entitled "D^4 Channels" which appears in this issue.

It is anticipated that some development will be initiated toward providing PCM on microwave. Digital microwave equipment is expected to be less expensive than present commercially available analog microwave equipment. At present, Western Union has a great deal of FDM analog microwave equipment in service. PCM on analog microwave can provide significantly better performance with less maintenance required. While PCM may require more bandwith than FDM on microwave when deriving voice channels, this bandwith gap can be narrowed considerably by using multilevel coding. It should be pointed out that PCM has a significant advantage if the traffic load is largely digital.

Furthermore, in all FDM systems there is a serious problem with system loading. A system that is carrying a small telegraph or data load mixed with a large voice load can use a loading as high as −8 dBmO. A system that may be assigned to carry a 100 per cent data load may necessitate reduction of the maximum loading to −15 dBmO. This results in a lower signal to noise ratio. While such systems do a remarkably good data transmission job, a PCM system allows a maximum loading independent of the type of input signal without intermodulation distortion. Another feature found in the PCM is a "universality" of channels, i.e., all channels are equally good and can be assigned at random to any standard service without restrictions as to "end channels" etc.

The most outstanding advantage of PCM over FDM on microwave is the capability for a better level stability by PCM even though the microwave system itself varies widely because of fading, combining and maintenance activity.

In conclusion, it has been demonstrated by this service trial and supported by theoretical considerations that PCM has significant advantages, in performance operations and in maintenance of equipment, over FDM on both cable and microwave radio. It can be shown that it is more economical too. However, this point must necessarily be the subject of another article. For short haul operation where FDM has never been successful with multiple physical cable pairs, PCM has been making significant inroads.

Acknowledgements

The authors wish to acknowledge the contributions to this project of many people in the Technical Facilities Department whose extra effort made it possible to accomplish this service trial in the shortest possible time, so that the advantages of PCM could be demonstrated and then used elsewhere throughout the Western Union nationwide communication network.

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PCM — D^4 Channels
(Derived Direct Digital Data)

D. J. Kostas and R. B. van Gelder

The T1 carrier system is a pulse code modulation (PCM) transmission system which transmits 1,544,000 time slots per second. As described in the previous article, time slots in the standard T1 terminal are allotted to twenty-four voice channels for digitally transmitting analog information.[1] The Western Electric T1WB-1 wideband data terminal transmits up to eight two-level 0-64 kilobaud asynchronous serial data, or facsimile signals, over a T1 carrier-repeatered line, while the Western Electric T1WB-2 data terminal transmits two 0-250 kilobaud signals.[2] Both of these type terminals provide D^4 channels. A D^4 channel is a digital data channel derived from a PCM line signal by entering the data directly, i.e., bypassing the analog processing operations.

Western Union engineers modified the standard T1 terminal to provide D^4 channel transmission of fifty-five teleprinters, in the T1 time slots allotted to only one of the twenty-four voice channels. Any number of voice channels can be converted to teleprinter channels in this manner. Before a detailed description of the design implementation and testing of this development is given, the theory and techniques applicable to D^4 channels, in general, will be summarized.

D^4 Channel Theory and Techniques

The techniques used for time division multiplexing of asynchronous binary data streams depend mainly on the data rates of the tributary data streams relative to each other and to the main stream, the multiplexer cost, the flexibility, the line efficiency and the reliability.

If the tributary data streams have only slight differences in their bit rates, or if their rates can be approximately expressed as an integral multiple of some basic data rate, a practical multiplexer could be designed by occasionally inserting a pulse, (pulse stuffing), or a group of pulses, (byte stuffing), in each tributary data stream, so as to equalize the data rates.[3]

One of the tributaries is a control data stream that is used in common by all other tributary streams to signal the demultiplexer the location of the stuffed bits or bytes. An elastic write-read buffer store and a voltage controlled oscillator can be used at the demultiplexer to remove the time gap created by the removal of stuffed bits or bytes. In general byte stuffing systems require less control channel capacity while bit stuffing gaps are easier to smooth out and require less memory

Stuffing techniques yield efficient multiplexers, efficiency being a measure of the number of mainstream time slots that need be transmitted per bit of data. Unfortunately implementation cost of the logic, for insertion and removal of the stuffed bits, makes this method of multiplexing relatively expensive for short and medium haul as well as for low and medium speed data traffic. Another disadvantage of the above technique is speed sensitivity. One cannot easily implement this multiplexer for variable baud rate traffic.

The T1WB-1 and T1WB-2 data terminals are variable baud rate multiplexing systems using T1 repeatered lines. Multiplexer flexibility is obtained at the cost of line efficiency. The design of these multiplexing systems is as follows. Using the T1 repeatered lines, the 1,544,000 time slots are systematically allotted to the tributary data streams.

1(b) is encoded into three substream digits, shown in Fig. 1(c). The first digit of the encoding indicates to the receiver, whether a transition has occurred, the second digit describes in which half of the timing interval the transition occurred, and the third indicates the polarity of the transition. Note that by restricting the maximum baud rate of the tributary stream, another transition does not occur until the three bit encoding of the prior transition is transmitted. The decoder converts the three digit codes back into data transitions in Figure 1(d).

Since the transition timing is quantized to within one half of the substream bit interval and the minimum time interval between data transitions is three equispaced substream bit intervals the theoretical (assuming very steep rise times at encoding) maximum transition timing jitter is $\pm 1/12$ or ± 8.33 percent at the limiting baud rate.

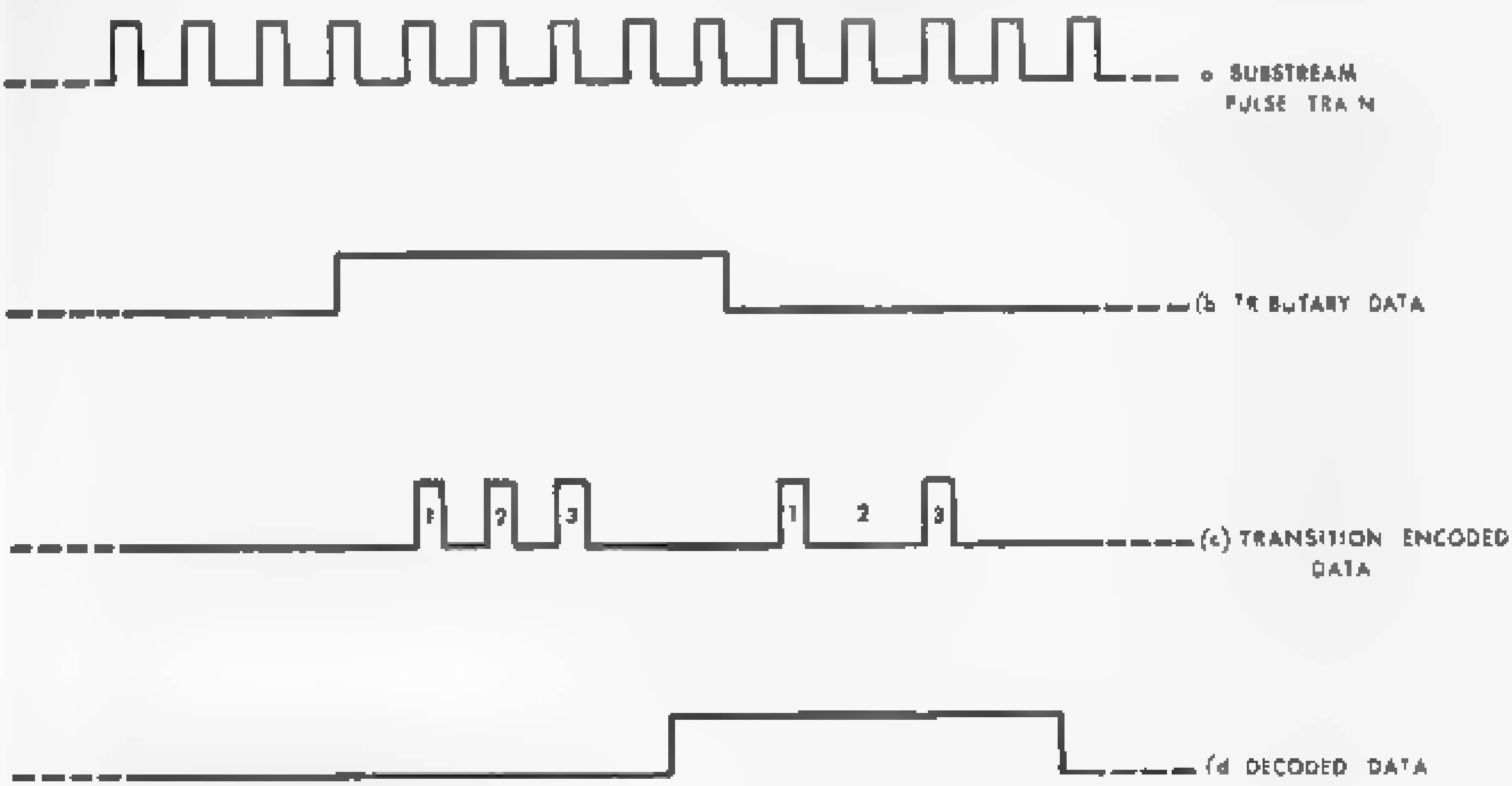

Figure 1—Timing Diagram for Transition Encoding-Decoding

Figure 1 illustrates a timing diagram for transition encoding-decoding. An appropriate sub-multiple of the T1 clock, as shown in Fig. 1(a), serves as the information carrying substream for one tributary data stream. Every transition of the non-return to zero tributary data shown in Fig.

To overcome this timing jitter limitation of T1WB-1 and T1WB-2 a four digit encoding or higher is required. This will increase the encoder-decoder logic costs and decrease the line efficiency. If line efficiency is not a prime consideration, the improvement in timing jitter can be obtained, with

no increment in encoder-decoder cost, by merely increasing the length of the encoded word; the extra digits are not used to describe the transition timing.

For example, a four digit encoding will have ±1/32 or 3.1 percent maximum theoretical timing jitter when two digits are used to describe the transition timing and 1/16 or ±6.25 percent maximum theoretical timing jitter when only one digit is used for timing information.

If minimization of multiplexer cost is the prime factor, the cheapest but least line-efficient method for multiplexing asynchronous data streams is simple sampling.

In simple sampling, the two level input data is sampled at a selected substream rate and each substream digit carries polarity information to the receiving end. To keep the maximum timing jitter low, the tributary data baud rate should be much smaller than the substream rate. A rate ratio of forty can yield ±2.5 percent maximum theoretical timing jitter at 2.5 percent line efficiency.

System Engineering Considerations

In designing a multiplexing system for telegraph and data up to 4800 baud, using T1, traffic demands, timing jitter, line efficiency, implementation costs, reliability and channel unit standardization factors interact. One concludes that the pulse and byte stuffing techniques are impractical at these data rates. Furthermore, transition encoding can be advantageously employed for medium and long haul traffic, while simple sampling proves-in best for short haul traffic.

Considerations of traffic demand, flexibility and reliability dictate that for best utilization of the T1 terminal the transitional encoding multiplexer be designed so as to be used on a per T1 voice channel basis.

From standardization and line efficiency tradeoffs it was decided to design one channel unit for all teleprinter transmission, 0-200 baud, a second channel unit for 0-1200 baud, a third channel unit for 0-2400 baud, and a fourth channel unit for 0-4800 baud. The option of transmission of data clock was also included with the third and fourth channel units. The encoded four digit pulse train that is transmitted under this option describes respectively, the occurrence of the negative clock transition, half-interval time, quarter-interval time and state (mark or space) of the data stream at the negative clock transition. All of these were designed.

Design of the 0-200 Baud D⁴ Channel

A teleprinter multiplexer using transition encoding designed and implemented by Western Union is shown in Figure 2. Fifty-five teleprinters (0-200 baud) are multiplexed into the j^{th} voice channel.

The D_n and E_n, D_n' and E_n' switches provide the j^{th} channel with a 7-digit sequence (byte) which occurs once every frame. Electronic switches A_k, B_k, A_k' and B_k' distribute the j^{th} channel bytes to 8 independent groups of sources and sinks.

Each time the channel counter is on the j^{th} position, information concerning a different group of seven teleprinters is transmitted. One of the 56 teleprinter time slots is used for the transmission of the subframing sequence. An all one sequence cannot describe teleprinter transitions and is used for synchronizing the Receiving Distributor switch, A'_k, to the Transmitting Distributor Switch, A_k, and the Receiving Distributor Switch, B'_k, to the Transmitting Distributor Switch, B_k. The two D_n switches are synchronized by the main T_1 Carrier Framing Control. The two E_n switches are similarly synchronized.

The subframe detector and control, shown in Figure 2, is designed so that the probability of false alarm (going into frame search mode erroneously) is small. The probability of out of frame detection within a couple of transitions is close to unity.

Normally the subframing sequence consists of all "one" digits. The Subframe Detector examines three subframe digits at a time and will decide the system is out-of-frame only when three successive "zeros" are detected. Isolated digit errors will therefore be ignored and will not cause frame search. When three successive zeros are detected, the Subframe Detector inhibits the advance of the A'_k Receiving Distributor Switch while checking each possible subframe bit position for a one. The checking process is continued until a subframe bit position is found which is transmitting a one, 1. The A'_k Receiving Distributor Switch is then started and the Subframe Detector tracks this bit position to ascertain whether or not an all one sequence is present. If the all "1s" sequence is present, no further action is required. If the all one sequence is not present, the framing process repeats.

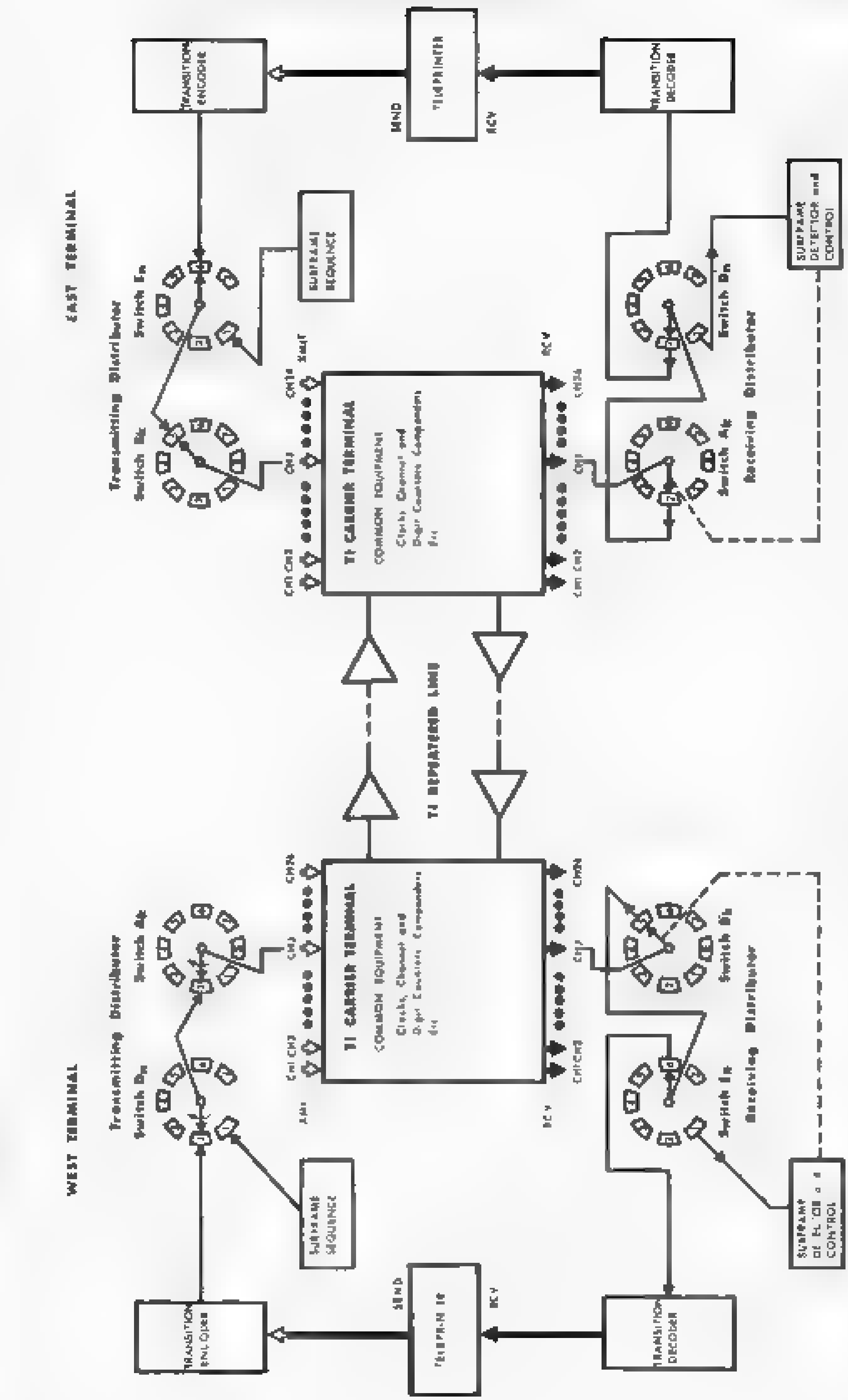

Figure 2—T1 Carrier System using Voice Channel Multiplexing for Transition Encoding-Decoding

Figures 3 and 4 show logic diagrams of the teleprinter transition encoder and decoder.

Each data transition is encoded into a four digit word. Each digit respectively describing, transition occurrence, half-interval time, quarter-interval time and transition polarity. When a transition occurs the Transition Detector output immediately presents the Transition Occurrence Bit Cell of the Shift Register. If the transition was in a positive direction, the Transition Polarity Bit Cell is also immediately preset. At four equally spaced bit times of the subframe interval, the Transition Detector output is gated to the ¼ Interval Bit Cell and ½ Interval Bit Cell. At a particular time designated, j D, A, the Shift Register is clocked and the Transition Bit is placed into the T1 bit stream. At subsequent j D, A times, the ½ interval, ¼ interval and polarity bits respectively are shifted into the T1 bit stream.

The ¼ and ½ Interval Bit Cells have four possible states, one for each quarter of the subframe interval. The ½ Cell is preset if the transition occurs in the first half of the subframe. The ¼ Cell is preset if the transition occurs in the first ½ of either half of the subframe interval. Note the feedback from the ½ Interval Cell to the ¼ Interval Cell input which prevents the ¼ Interval Cell from being preset if the transition occurred in the second quarter of the subframe interval. Note also that the output of the Transition Detector is inhibited during Shift Register output to the T1 bit stream.

At every subframe time, j D, A, a bit describing a portion of the transmitted teleprinter encoded transition is placed in the T1 bit stream. At every corresponding time, j D', A', in the Re-

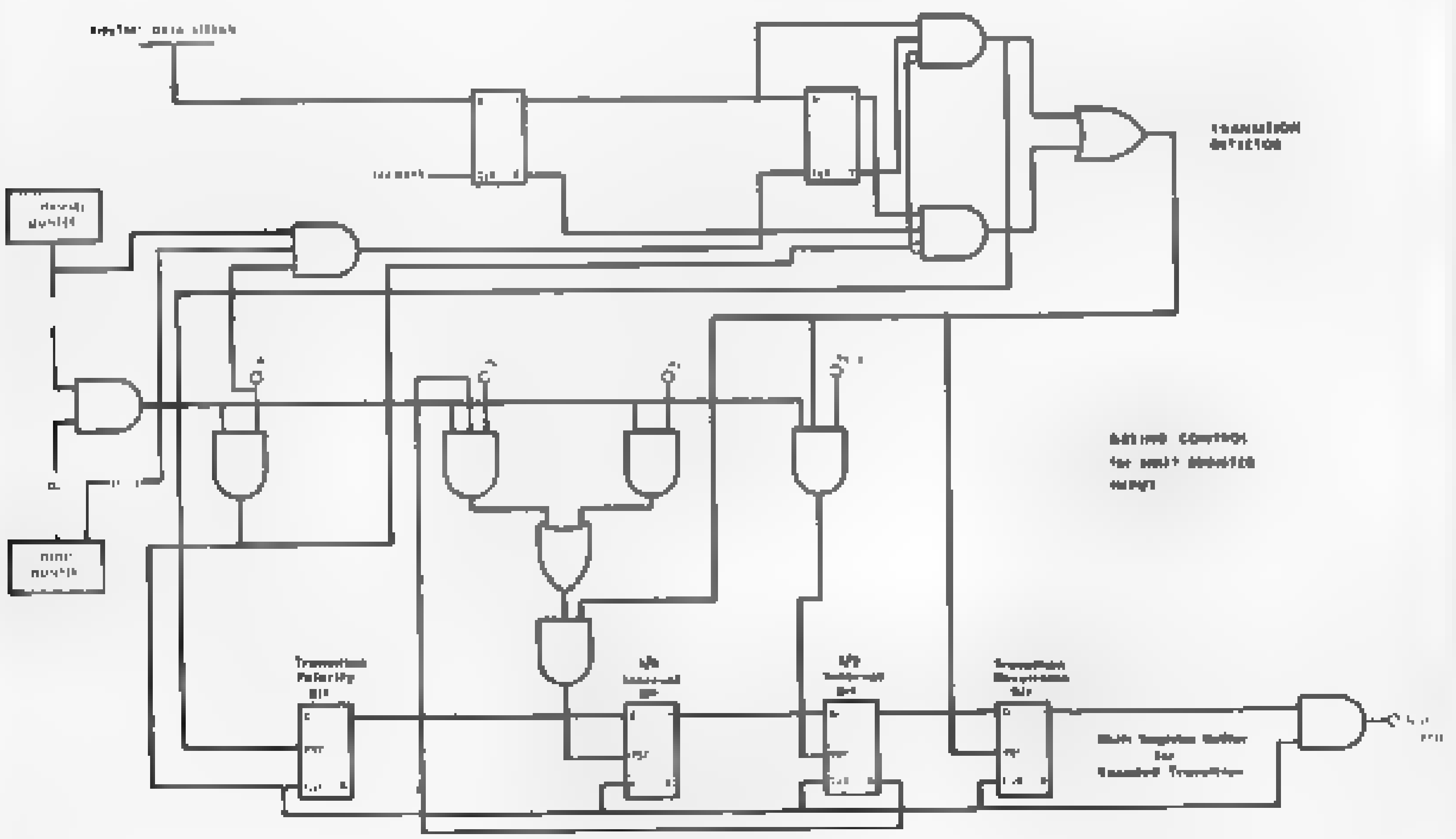

Figure 3—Logic Diagram for the Teleprinter Transition Encoder

ceiver, this bit is shifted into the Receiver Input Shift Register. The Transition Occurrence Bit is used as a flag bit to mark the beginning of each encoded transition. When the Transition Occurrence Bit reaches the fourth cell of the shift register, the Transition Decoder gates cause a pulse to be emitted at the appropriate time in the subframe interval. Signal polarity is assigned to the output pulse through the input gates of the Output Flip/Flop. The Output Flip/Flop maintains the last signal condition set into it, yielding a non-return to zero output for teleprinter operation.

Note that the subframe counter output are chosen to be those which mark the center of each quarter subframe interval; the quarter interval being the one which was used to encode the signal transitions at the transmitter. By placing the reconstructed transition at the center of the quantizing time interval, the output peak jitter is cut in half relative to the value which it would have if the output transition were assigned to one end of the subframe quarter interval.

Reset of the Receiving Input Shift Register is accomplished at the end of the subframe. If a bit is in the Transition Occurrence Bit Cell, the first three cells of the shift register are cleared. The Transition Occurrence Bit Cell is cleared one bit time later. The register is now prepared to receive a new four bit word.

Decoder synchronization will take place within three transitions of the input data at system start up when the input signals are 200 baud or less. For inputs above 200 baud but not exceeding 250 baud, synchronization will take somewhat longer depending upon baud rate and character structure.

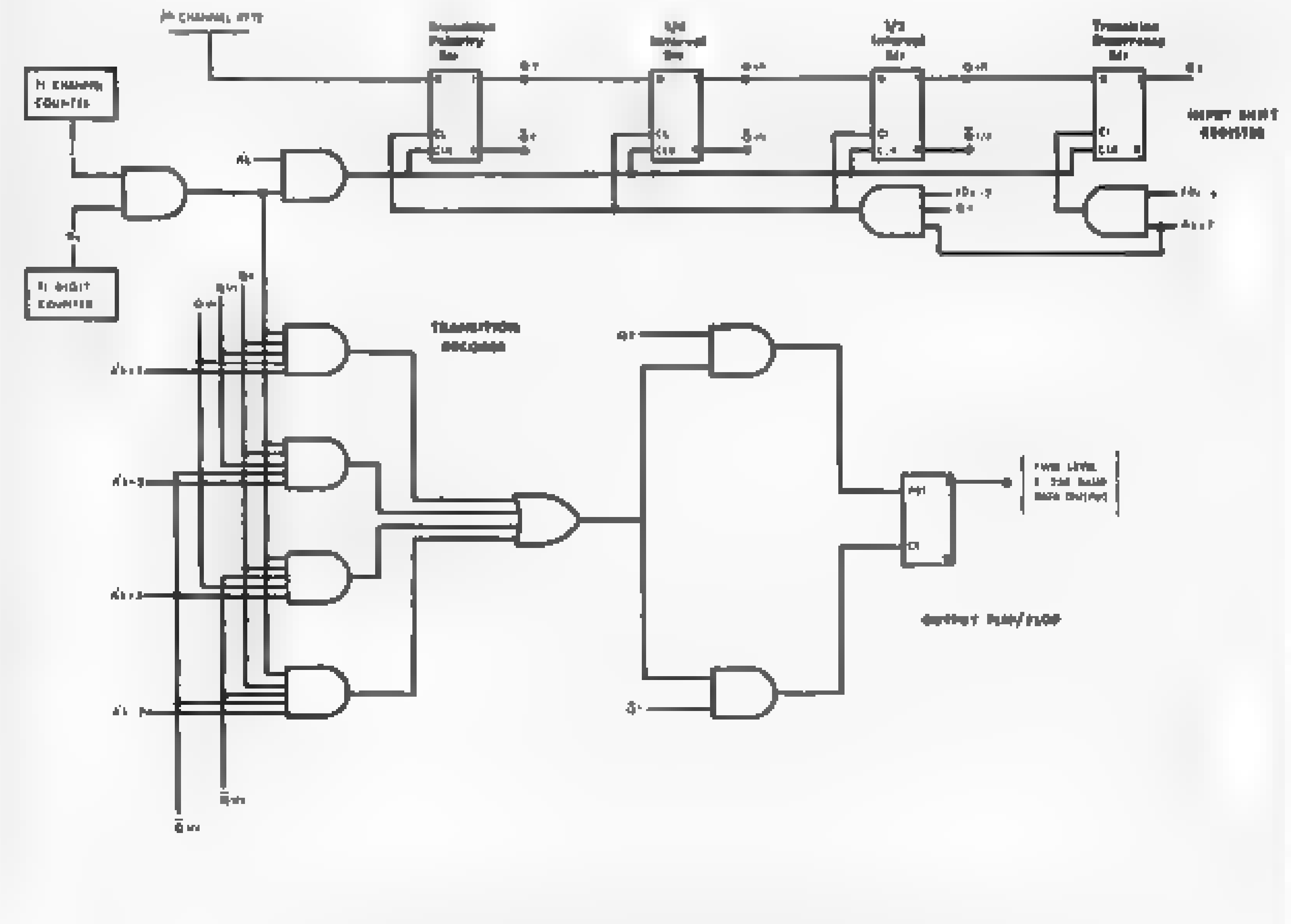

Figure 4—Logic Diagram for the Teleprinter Transition Decoder

Implementation of the 0-200 Baud D⁴ Channel

In order to demonstrate the Transition Encoder/Decoder operating compatability with a T1 Carrier System, a voice channel T1 Carrier Terminal was equipped with additional common equipment and a Transition Encoding/Decoding Channel Unit for 12 volt polar DC inputs up to 250 bits per second. The resultant signal was successfully transmitted over approximately 20 miles of T1 Repeatered Line, as shown in Figure 5.

The availability and low cost of integrated circuits are attractive inducements to their use in digital logic circuit implementation. Furthermore, integrated circuits are convenient for achieving a working laboratory model quickly. For the implementation of the Transition Encoding scheme described in the previous paragraphs the Transistor-transistor Logic (TTL) variety of IC was chosen primarily because of its low output impedance in both high and low output states. Further, the relatively high speed of TTL simplifies the problem of signal delay when several stages or levels of logic elements are cascaded.

In the process of designing the logic for the Transition Encoder the logic diagram was translated into a new logic diagram compatible with the NAND gate of the TTL ICs. This step is easily accomplished and illustrates the convenience with which ICs can be applied. In relatively small logic systems such as the one at hand, the logic diagram becomes the circuit schematic with very little effort.

Interface Considerations of the 0-200 Baud D⁴ Channel

The Transition Encoder/Decoder interfaces with an existing T1 Carrier Terminal at the common equipment interface. The Transition Encoder may be thought of as a digital rather than an analog channel unit. Transmission of digital data by transition encoding makes more efficient use of the available line digits than transmission of data by analog encoding. Therefore, many Transition Encoding Channels may occupy the time slots of one voice channel. In the system shown in Figure 5, fifty-five D⁴ channels occupy one voice channel's time slots.

One additional piece of common equipment was provided to subdivide the T1 Carrier Frame into a number of subframes commensurate with the bit rate of the applied data. A counter whose input is one pulse per frame is used as a divider to derive the subframes. The counter is made up of JK flip flops in one, two or three binary stages. This configuration is flexible in allowing for addition of control functions. Furthermore, it is more economical than the shift register or ring counter approach.

In order to facilitate the interfacing of the Transition Encoder with an existing T1 Carrier Terminal it was desirable to duplicate certain of the common equipment counting functions to make readily available digit time slot signals for control of the per channel Encoder operation. This duplicate counter equipment operates in parallel and in synchronism with the T1 Terminal common equipment. This duplication equipment would not be needed in a final design.

The interface with the T1 Line was accomplished by inserting the Transitional Channel pulse stream into the common pulse stream of the T1 Terminal in the proper time slots. Once the combined digit stream has passed through the T1 Terminal common equipment, the pulses inserted by the Transition Encoder Channel are indistinguishable from pulses of other channels. They are processed and transmitted to the T1 Line in the same manner as pulses originating from voice channels.

On the receiving end the received pulse stream is monitored by all the Transition Decoders. Each Decoder has its input gate opened at its assigned time slot so that information from the received pulse stream will pass into the Decoder. As on the Encoding side of the system, duplicate, synchronous counter equipment is employed to facilitate the gating control for all Decoders. Again this duplication would not be necessary in a final design.

Testing the 0-200 Baud D⁴ Channel

The performance criterion of a digital channel is error rate; i.e. how often the output is in disagreement with the input. This criterion is usually expressed in terms of frequency of error. Any degradation of Transition Channel performance must necessarily come from digital errors originating either on the T1 Line or as a result of a digital circuit malfunction in the terminal equipment. By monitoring the rate at which bipolar errors are committed on the T1 Line with the Line Error Detector provided in the New

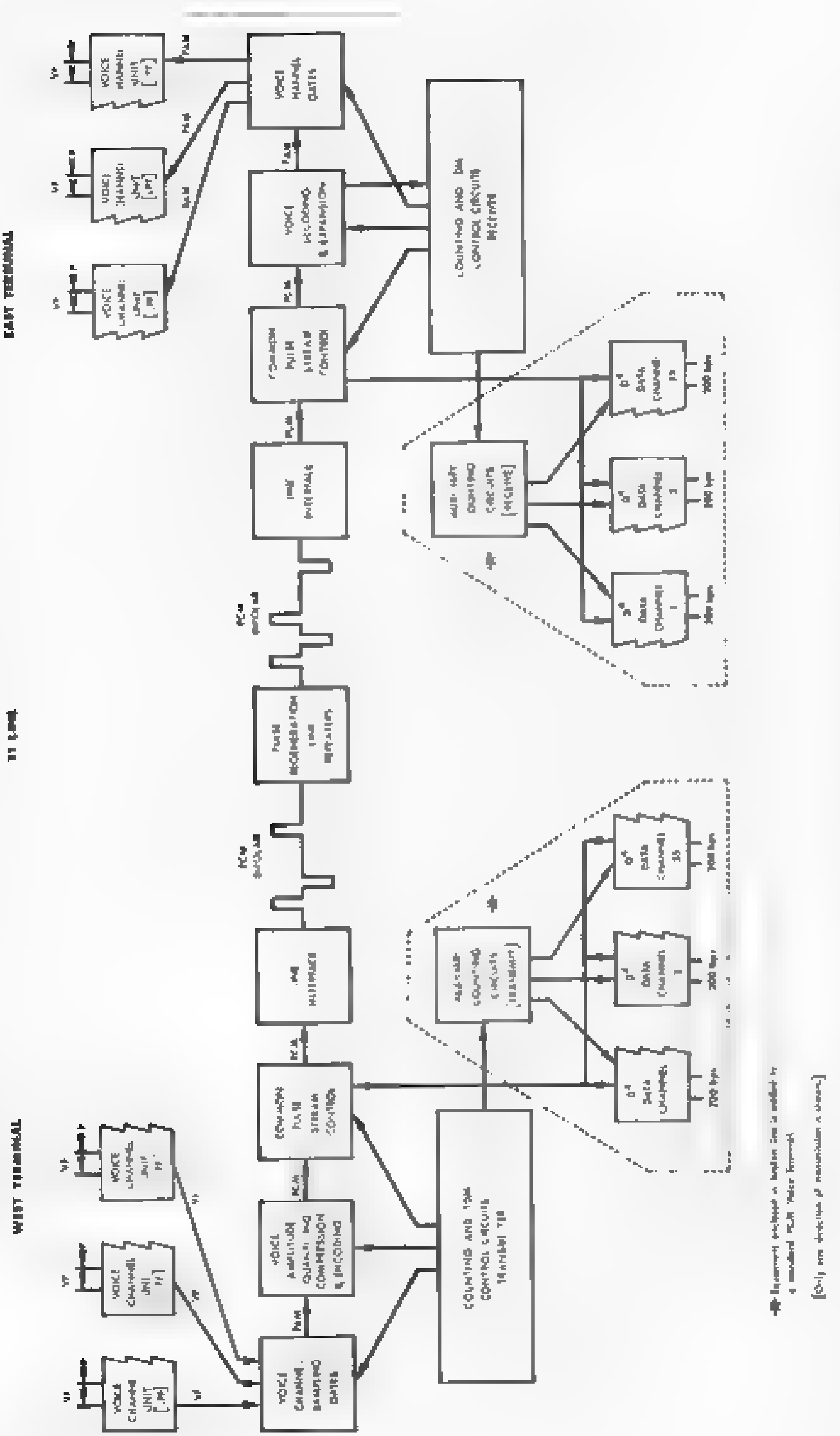

Figure 5—Block Diagram of a PCM System with 55 D⁴ Channels for One Voice Channel

York Newark operating system, it was determined that the line error rate is equal to or better than one in 10^6 bits. In general this error rate as well as that caused by digital circuit malfunction is a couple of orders of magnitude smaller than the overall error rate encountered in teleprinter transmission.

From the overall error rate point of view this T1 transmission link does not directly cause any errors. It does cause timing jitter, by its time quantization. In digital channels error rate is usually estimated from data pulse distortion measurements. The four digit Transition Encoder gives a peak value of time jitter (peak distortion) of $\pm$ 3.1 percent at the maximum rate of 250 baud.

This was readily confirmed in the model by taking measurements with a Digitec Teledata Analyzer and independently with a Tektronix 647A Oscilloscope. This amount of jitter is insufficient to cause errors in a single span or even in several spans in tandem. Note also, that the D^4 channel output is a reshaped rectangular waveform.

Performance in the presence of noise is an area of special interest. The most troublesome signal contamination comes from mechanical contact bounce in various types of teleprinter transmitters. Contact bounce is frequently a source of considerable annoyance at the input to a solid state circuit. While contact bounce duration is usually a small percentage of the minimum time between successive transitions, it can be most hazardous to the Transition Encoding circuits. To the Transition Encoder Channel Unit contact bounces will appear to be a series of closely spaced transitions simulating a data bit rate which is in excess of the maximum design rate. When the design bit rate is exceeded the error rate of the Encoder increases drastically, rendering its output useless.

One particularly hazardous situation was encountered wherein a tape distributor produced short dropouts (equivalent to contact bounce) between each pulse of a series of non return to zero (steady marking) pulses.

Contact bounce or very short duration dropouts are not likely to be recorded by an electromechanical device such as a teleprinter select magnet mechanism which typically has a response time well in excess of one millisecond. The same characteristic response of select magnets can be obtained by using other analog low pass filtering techniques. A simple solution to this problem is to have the Transition Encoder not respond immediately but wait for an interval of one millisecond to ascertain that the transition is not of a transient nature. Note that this time duration was made to be in accord with select magnet response time. If the transition persists for this interval, then it is taken as valid, and the Transition Encoder places the transition information into the common bit stream to be transmitted.

Other Applications of D^4 Channels

Most Western Union traffic consists of binary digital data at various speeds. Therefore, many types of D^4 channels are needed.

D^4 channels for 2400 baud and 4800 baud have been designed and were mentioned earlier in this article. The design of a synchronous 40.8 kilobit per second D^4 channel using pulse stuffing which occupies a single T1 voice time slot has been accomplished. Likewise, a D^4 channel for extending local telex subscriber loops has been designed. Presently a D^4 channel for Desk-Fax signals is being designed. All of these will be implemented in the near future.

Presently, a sizable effort is being funneled into the development of another PCM terminal concept. This concept is called MINI-T which is shorthand for minimum cost PCM terminal. This terminal also accommodates a mixture of voice and data. However, it uses simple sampling to process the data as economically as possible. Its primary field of use would be for distances where terminal cost dominates prove-in equations, namely short and medium haul. MINI-T has so many ramifications that it can only be fully amplified in a separate article.

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Advantages of PCM

In summary, the first and second articles in this issue of the TECHNICAL REVIEW have emphasized the three basic advantages of PCM: 1) it is digital in nature, 2) it ideally interfaces with data processing machine, and 3) it is flexible to accommodate all future data requirements.

- PCM obviously shares much modern digital technology with the data handling field. The digital nature of PCM leads directly to the heavy use of integrated circuits. The rapid advances in the state of the monolithic semiconductor art will be a distinct advantage to future PCM designs. The techniques and hardware of digital logic circuit design which have evolved in the last ten years in the computer fields are directly applicable to PCM.

- It is a fact that the "interface" between an all digital transmission system and the machines which originate and process data is a better matched interface than those which have existed heretofore.

- The rapidly increasing use of digital data, both low and high speed, has already created requirements for higher speed, reliable data transmission. The requirement for high speed digital transmission, flexible enough to allow for multiplexing numerous tributaries of various speeds will increase exponentially in the years to come.

Our Customer Says:

Western Union's 301 Switc meets reliability requiremen

by Norman M Spiva

[redacted]ger
Methods & Research Dept

Mr Spiva has been manager of the Methods and Research Department of D&B since 1959 and has been aware of the performance of previous Western Union systems at D&B.

Our management at Dun & Bradstreet installed the Western Union 301 computerized message switching system in 1965, with the primary aim to achieve faster, more efficient service on subscriber credit inquiries. These inquiries had reached such proportions that it was almost impossible to handle the heavy load effectively with a manual switching center set-up

During the three year period the computerized system has been in operation, it has performed very satisfactorily in terms of traffic handling transmission accuracy, cost per message and reliability. We have been able, as we intended, to substantially improve service to our customers.

Dun & Bradstreet has been engaged in gathering and disseminating business information since 1841. In recent years Dun & Bradstreet has diversified its operations into a wide range of business information systems, services, and sciences, including publications and services in the areas

ching System
nts of
Dun & Bradstreet, Inc

Six teleprinter ASR units are in constant operation in the main teletype room at Dun & Bradstreet headquarters where all subscriber inquiry traffic for the New York area is handled. Headquarters administrative traffic also enters the system here.

of Economics, Marketing, Sales, Credit, Education, Finance and Research.

From an operational standpoint, Dun & Bradstreet divides the U.S. into geographic areas. At each location a Dun & Bradstreet office is responsible for gathering information on all businesses located in that area and processes requests from Dun & Bradstreet customers for information on those businesses.

When a Dun & Bradstreet office receives a request for information on a business located outside its own "reporting area," the inquiry is routed via teletype to the Dun & Bradstreet office that serves the area in which the business inquired upon is located.

With volume of inquiries mounting steadily and our customers' need to receive information faster, we have developed automated systems to handle the increased traffic and speed requirements. Consequently, Western Union's 301 Message Switching System was chosen as part of our

The switching center attendant checks an hourly, computer-generated status report, generated by the computer at the New York headquarters of Dun & Bradstreet.

automation. We had two previous Western Union systems for handling inquiry traffic. The new computerized 301 switching system, cutover in November, 1965, was the first Western Union computer controlled industrial teleprinter system.

Because of our past experience with Western Union, and their capability in record communications, Dun & Bradstreet worked with Western Union to design the new system to our special requirements. They provided the engineering experience required to modify trib-station and switching center equipment, as well as helped to design and build new equipment where required. In addition, Western Union had the capability for computer programming. Therefore, Western Union assumed full responsibility for implementation of the system. This was a definite advantage for us to have Western Union offer the single responsibility for the total system.

We did not hesitate to take certain calculated risks in the design and installation of the system. We demanded—and received from Western Union—sufficient system reliability to preclude the necessity for back-up computer facilities. In spite of having no back-up computer, the system has operated with 98 percent up time. This is particularly good, since the system is a tape oriented system requiring the reading of the entire daily tape journal if the system fails and recovery is required.

When message format was being developed, Dun & Bradstreet insisted upon the briefest possible header because even one unnecessary character per message would reduce the message capacity of the system by 40,000 messages annually. As a result, Western Union gave us a nine-character (average) header format (11 characters for priority messages). At the time our system was designed in 1964-65, this exceptionally brief header was roughly 15 to 40 characters shorter than that used for the header in many similar systems then on the market. This factor alone, "the new header," increased the message handling capacity of our network by about 750,000 messages annually.

The capability for sequential message numbering and station polling before message transmission were programmed into the system—and these and other programming features have produced a record of *"no lost messages"* during the system's operation.

In all cases, careful planning in the design stage paid off in system effectiveness.

System Hardware

Our Western Union 301 system comprises one CDC 8090 computer, one line multiplexor, one high speed 1200 baud concentrator and 12 directly connected Western Union Plan 117, 75 baud, 100 wpm full duplex way circuits. The concentrator, located at Indianapolis, services an additional 8 full duplex 100 wpm circuits with an average of 6 stations per circuit.

Peripheral equipment includes two supervisor ASR positions, one tape controller, five tapes, one console with paper tape reader/punch. Trib-station terminal equipment comprises a Model 28 ASR—Type 2C; selectors are electro-mechanical Plan 117. The code used is 5-level Baudot.

Our network has been expanded from 84 stations in 1964 and now connects a total of 101 stations in 90 Dun & Bradstreet offices to the computer located at our headquarters in New York. All communications control, and ancillary information processing, is performed by the CDC 8090. The tapes used in the system include one for intercept, one for overflow, one auxiliary (for use when overflow or intercept are being read into the computer), one for loading the system program, recovery program or retrieval from prior day's journal.

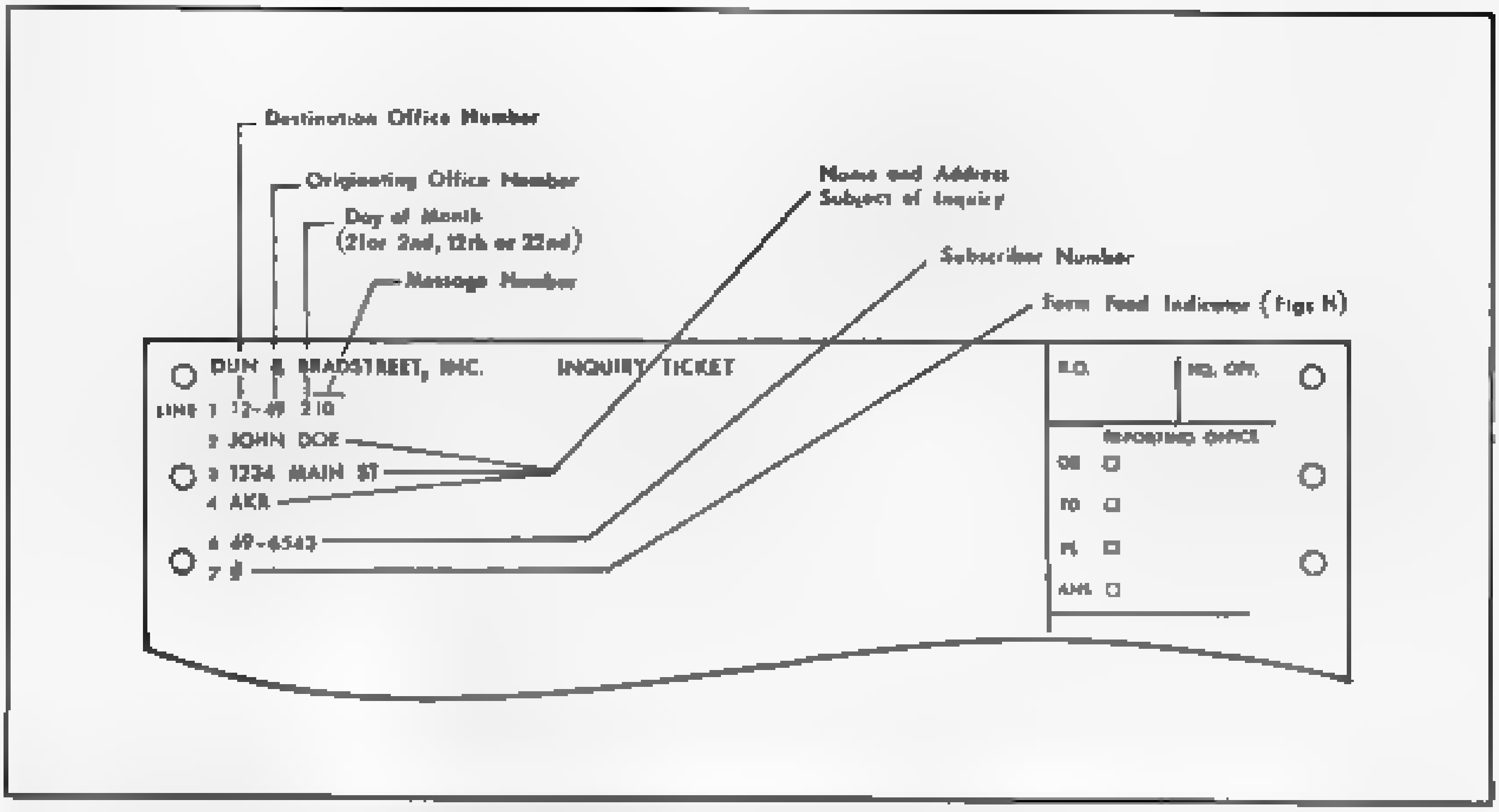
Message Volume

Roughly ninety percent of the traffic run through the system consists of subscriber inquiries for information on business concerns, the remaining ten percent represents administrative and sales accounting messages.

Before the Western Union 301 switching system was installed, messages delivered in 1964-65 totalled 4,700,000. Traffic has increased an average of 365,000 messages annually during the past three years. This past year, the total delivered reached 5,800,000—or some 22,000 to 29,000 messages per day, delivered within our thirteen-hour operating day.

System Operation

All traffic between the computer and communications terminals is controlled by the computer. Stations are "polled" or invited to send (ITS) on input and "selected" (SEL) on output. Messages are received serially, and stored a character at a time in the Line Multiplexor for forwarding to the CPU.



The above Dun & Bradstreet inquiry ticket illustrates a typical address format on a message. The brevity of the header contributes substantially to system efficiency and economy.

Messages are processed on a first-in first-out basis, with a three level priority structure, which permits processing and delivery of priority messages ahead of normal messages. (Highest level, computer originated message; second level, office priority message; third level, office regular messages).

In the course of a working day, an average of 2,200 priority messages are processed.

All Messages Validated

Validation checks are performed on all messages, character by character, as received, for correctness of the header (address portion of the message). When an error is made at the sending station, or an error is encountered during transmission, the computer automatically stops its transmission, over the outgoing leg and stops the "offending transmitter" within 600 milliseconds (6 characters) of the error. In addition, an alarm lamp is activated on the teletype machine, and the computer automatically sends a message to the initiating office advising the reason for rejection. This later message also includes the header portion of the rejected message.

The computer also delivers a printout of each such error message on a Supervisory ASR unit at the switching center. Thus, the Center Attendant is constantly apprised of the current status of the operations.

Valid messages at this point in processing are not logged, but are stored on the drum, which is the in-transit storage device. These messages are assigned unique identification numbers on input, and the computer checks each input number to ensure no lost messages.

Message Routing

Messages can be routed by single address, multi-address or group code. The message and input/output message data is logged upon final delivery on the Journal magnetic tape. Output goes to the addressed station, unless it is on intercept storage, or alternately routed to a designated station. On-off intercept is accomplished either automatically on selection, or manually by the Center Attendant. Alternate routing is always initiated by the Switching Center Attendant by use of a command message.

There are two Switching Center Attendants at the New York switching center, who share manual control of system operations. The Attendant's role includes changing the polling pattern/cycle, inserting system date/time, alternate rounting, intercept, retrieval, system start-up, shutdown and recovery.

Unique System Features

Our custom-designed system has two unusual features which account for the overall high-level system efficiency

1. In addition to Western Union making certain engineering modifications in equipment, the program was written to include a number of features, including some innovations which increased circuit utilization. Four examples of these are

   a) Even though full duplex circuits and conventional 28 ASR stations are used, this system permits the receiving of answers back from selected stations before a message is delivered by the computer. This means that circuit time is never used to deliver messages until an answer back is received to assure that the station is up contains adequate paper, and is ready to receive the message

   The feature also permits the elimination of transmission of an automatic message number outgoing from the computer—which not only saves circuit time (the equivalent of 240,000 messages annually)—but also eliminates tallying of numbers by Dun & Bradstreet offices to assure that no messages are lost

   b) The same assurance of message delivery is provided even though each station is operated unattended for a minimum of 3 hours each day

   c) If an error is detected in an incoming message, the transmission is stopped within 600 ms. so that a minimum of circuit time is wasted on the transmission of erroneous messages

   d) The system was designed on the basis of rejecting a minimum number of erroneous messages to the Center Attendant. Instead all erroneous messages, except one are rejected back to the origination point for correction and re-transmission

The uniquely brief header design was mentioned earlier—and it has been a major contributing factor to system effectiveness. Ours is still one of the most efficient way circuits in operation today. The short header, combined with fast turn-around time and the features just listed, achieves maximum circuit utilization. As for turn-around time, on the outgoing leg of the circuit, the time required to terminate one transmission and select the next station to receive, including answer back, ranges from 350 to 600 ms depending upon whether the incoming leg is idle or busy. This 350/600 ms contrasts remarkably with the time of 13,000 ms for the previous Plan 111 system and the 2500 ms under the more recent Plan 115

2. Simplicity of computer center operations and supervision is another advantage of our present system

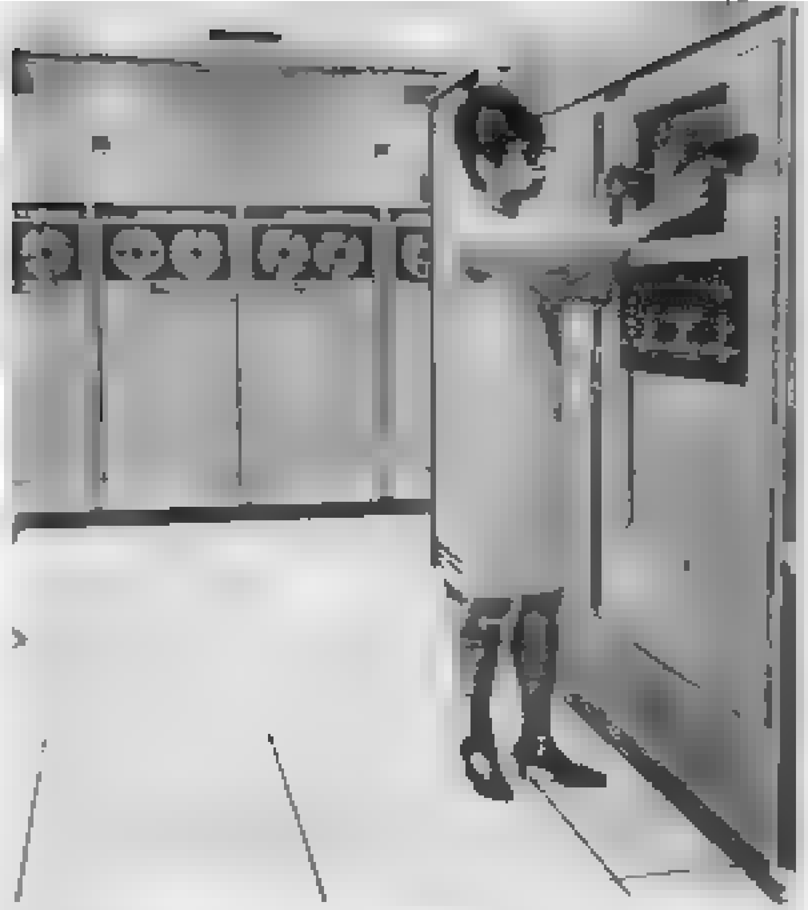
   Only ten computer command messages

The Magnetic Drum Memory unit is the in-transit storage device used in the Western Union 301 System; its capabilities include a capacity of up to 524,288 characters, and an average access time of 17.3 milliseconds.

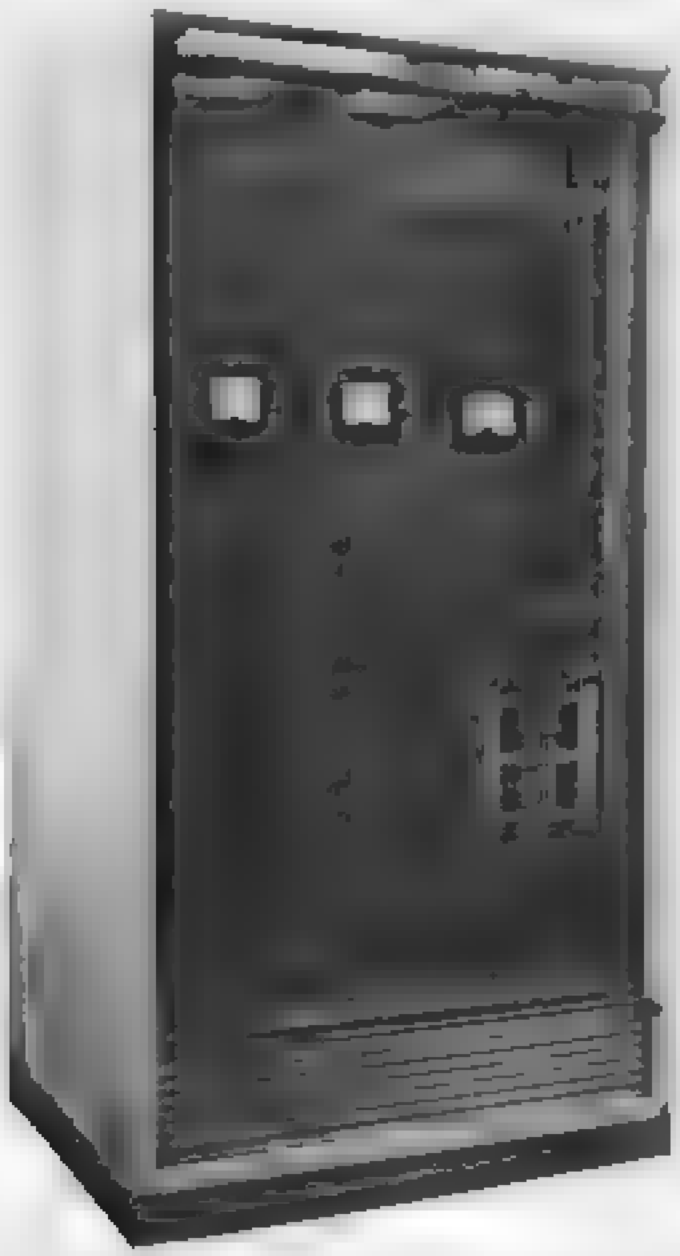
each less than twenty characters in length—cover all operations. The Center Attendant is required to monitor only three types of messages

a) Service messages sent to out stations (covering invalid messages or routings)
b) Notice of circuit or hardware malfunctions
c) Hourly status reports

The regular status report, which is provided either hourly or upon demand, provides data on each out station operation, including: messages transmitted, messages delivered, total messages queued up for delivery, and messages in intercept as a result of hardware or circuit trouble



Switching Center attendant, Pat Chu, loads a boot strap tape for calling in the "System Program" from the magnetic tape at the start of the day's operation at D&B.



The Communications Line Multiplexer, was designed by Western Union, for the Dun & Bradstreet 301 Switching System. It houses the communication line buffers, which are packaged in modules. Each module contains from one to eight line buffers, terminating lines of speeds up to 2400 bauds, and codes up to 8 bits per frame

Savings to Dun & Bradstreet

Due largely to the maximum efficiency achieved in the use of way circuits, the Western Union computerized switching system has effected a marked cost improvement for Dun & Bradstreet. The system was originally designed for 70-75 percent circuit loading—now and at peak traffic, circuits are operating at almost one hundred percent capacity. This, combined with the other features which contribute to maximum circuit use, has enabled Dun & Bradstreet to reduce the average cost per message by about one third over the previous system

A further important, though less direct, saving has been achieved through simplified Attendant operations. Approximately twenty-five percent of the Switching Center Attendant's time is required for actual supervision of the system. The remainder of the time is spent in handling other administrative functions

Western Union Handles Maintenance

Western Union is responsible for all equipment and program maintenance. Routine maintenance is performed weekly after operating hours, thus avoiding possible interruption of customer service. During the three years of system operation, only one service interruption occurred. With only one computer in operation and no back up computer, the 98 percent "up time" on the system speaks well for system reliability, and for Western Union's maintenance capability ■

COST EFFECTIVE Analysis
—our Management Tool

Gary R. Audin

Cost Effective Analysis is a management decision-making tool which presents a useful relationship between the system cost and the likelihood of the system achieving a preset goal. The end result is the minimization of the cost for a specified level of effectiveness.

To do this requires the comparison of some alternatives which can be directly related to each other. When the system parameters are well defined, this comparison is a simple one. However, some parameters are not easily defined.

With the continuously accelerating growth in data communications there is a need for management to make decisions on the effective use of transmission facilities.

Effective use can be obtained in either of two means; by increasing the number of circuits in use or increasing the transmission speed of a circuit. The first means is a matter of plant extension, the second is a matter of the capacity of a communication channel. This article will describe the possible limitations when transmission speeds are increased.

Data Transmission

Western Union's goal is to send as much data as possible at the lowest cost. The circuit or line, has the capacity for much higher speed with no increase in line cost, it is the terminal equipment that presents the cost problem. The cost per bit for terminal equipment increases, but the cost per bit for the circuit decreases as speed is increased. The total transmission cost is the sum of these two costs. The total transmission cost divided by the speed is a measure of the cost effectiveness of a modem-circuit combination. The effective speed is the data rate at which the cost/bit is lowest.

Transmission Speed Limitations

In 1948, C. E. Shannon developed a formula which fixed the maximum transmission speed of a communication circuit as:

$$\text{Maximum Transmission Speed} = W \log_2 (1 + S/N)$$

where: W — Bandwidth in cps
S/N — Signal-to-noise power ratio (absolute)
Speed — bits/second

for an arbitrarily low error rate. This formula is represented in Figure 1, as "Transmission Speed Limitations" as Maximum Transmission Speed. The number of bits of data that can be carried by a single cycle of signal is limited. The signal power must be greater than the noise level but it cannot exceed a specified channel limit. Within this range the resolution of the signal detection

circuit is limited by the noise, since the signals, corresponding to information content, must be separated enough so that the noise will not cause one signal to look like an adjacent one. The channel capacity limit is the product of the number of bits than can be resolved during one signal cycle and the bandwidth in cycles per second. Several idealized conditions are required to attain this limit, these are

a) Unity gain within the bandwidth W and zero gain at all other frequencies.
b) Linear phase shift across the bandwidth W
c) Elaborate encoding and decoding arrangements

Since the ideal requirements have not been met to date, only an optimum set of design considerations is possible. Even when assuming a perfectly implemented system and optimum signal shaping and filtering, an increase of 6 db in S/N is required to obtain a speed equal to the Shannon limit. This is represented by the curve for the "Present Design Limit," as shown in Figure 1. Another 2db of S/N is required to overcome the less than optimum results obtained when the hardware is constructed. The achieveable results are given in the curve, "Implementation Limit," in Figure 1. Therefore, practical transmission systems must operate to the right of this curve, i.e., at equal or greater signal-to-noise ratios for a constant speed. If the S/N ratio is constant, the system will operate below the curve, i.e., at lower speeds.

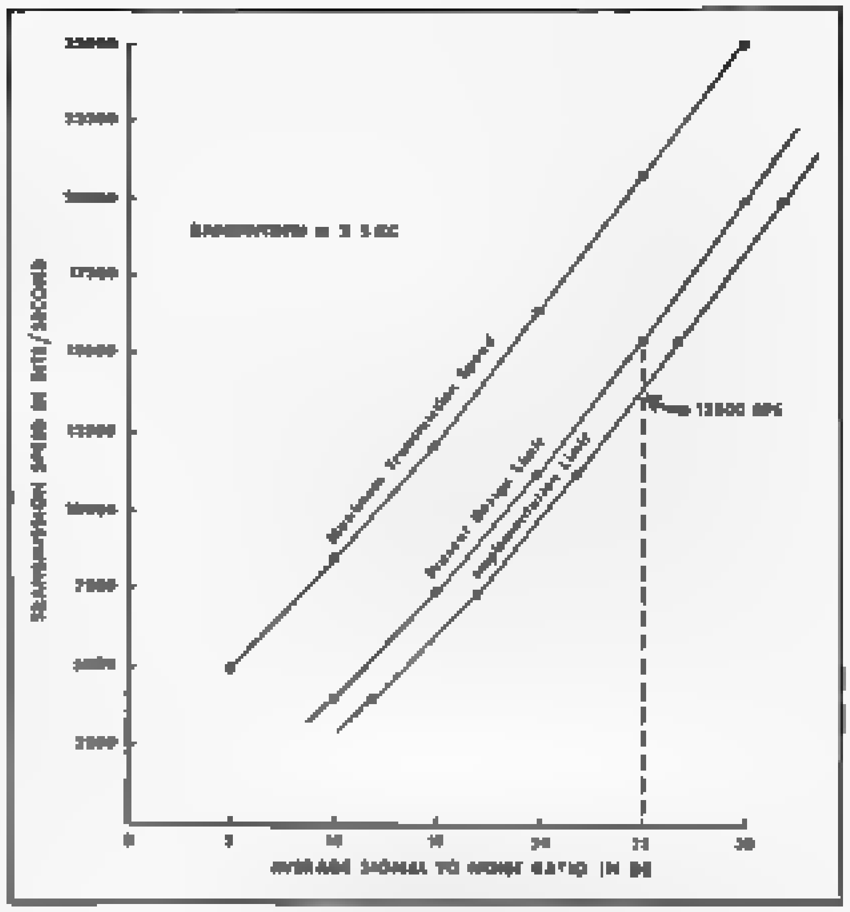


Figure 1—Plot of Average S/N Ratio vs Transmission Speed

Modem Costs

The "Implementation Limit" can only be met at considerable expense. The cost of a modem increases with increasing transmission speed for a constant S/N. By fixing the signal-to-noise ratio at 25db, a modem cost characteristic was developed. The modem cost includes a full-duplex data set, line equalizer, and encoder-decoders for error control. The error rate must be equally low for all speeds, otherwise, an objective comparison is not possible. The coder is not necessary for data rates of 9600 bps or below. Combining the price of all the equipment into a single cost allows a simplified transmission line cost to be developed. Normally, a voice circuit's conditioning, for higher speeds, is part of the line rental. This would require at least three different line rental curves, one for each data rate range.

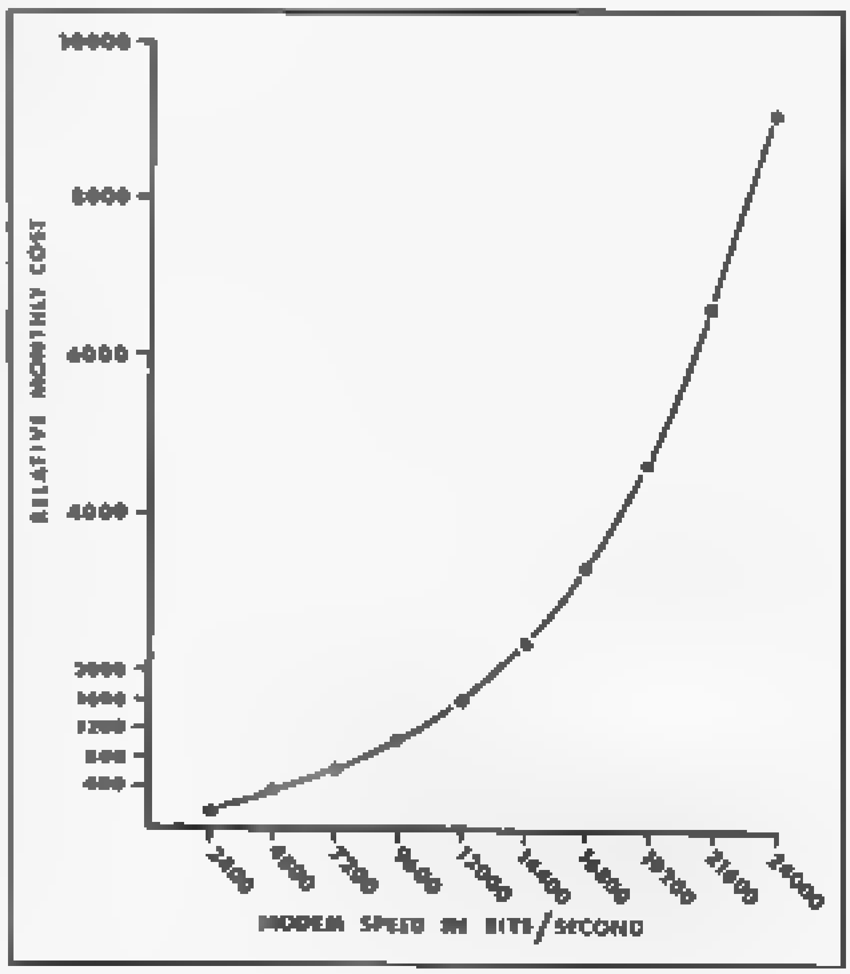


Figure 2—Plot of Modem Speed vs Relative Monthly Cost

The modem cost is represented by a monthly cost computed by dividing the purchase price by 50. This is the same as financing the purchase of the modem over approximately 10 years. The monthly maintenance cost is also included in the monthly cost. The purchase prices of available modems were used for speeds up to 9600 bps. At greater speeds the curve is extended exponentially as the speed reaches the "Implementation Limit."

The curve is developed from the formula,

$$\frac{\text{Modem Rental}}{\text{Month}} \quad 226.7\, e^{\text{[illegible]}} + 0.57B^{\text{[illegible]}} - 320$$

where B — bits per second

The cost has been normalized for easier representation of the values. In the Figure 2, the cost curve, Modem Cost/Month, has a useful range of 2400 to 24000 bps.

Transmission Costs

The voice circuit cost structure was developed from one of the references used in the design of Western Union transmission facilities. It is the internal company cost, not a tariff charge. The line cost, shown in Figure 3, is composed of a fixed termination cost plus a line cost/mile which decreases in increments as the length increases. The cost has been normalized to keep it relative to the modem cost. This monthly cost is defined as,

$$\frac{\text{Line Cost}}{\text{Month}} = 11.71\, M^{\text{[illegible]}} + 1.19\, M + 190$$

where M — miles

The useful range of the curve in Figure 3 is 100 to 3000 miles, where the curve is always within $\pm$ 3% of the relative cost.

Cost/Bit Characteristics

The cost effective transmission speed will be the speed at which the cost/bit is lowest. A full duplex transmission system is assumed. There is an optimum for each line length. The cost/bit is the necessary evaluation, since the total cost only increases with transmission speed and/or line length. The transmission cost/bit goes down as the line lengthens while moden cost/bit goes up with higher speeds. At some particular speed the total cost/bit will be at a minimum. At this point for a specific line length, the cost of transporting a bit that distance will be lowest.

The total cost/bit, C_T, is computed from the equation,

$$C_T = \text{Cost/Bit} = 2 \times \frac{\text{Modem Cost}}{\text{Month}} + \frac{\text{Line Cost}}{\text{Month}} \Big/ B$$

This is the cost of a line of a specific length plus two modems, one at each end. The equation may be evaluated as,

$$\text{Cost/Bit} = (11.17\, M^{\text{[illegible]}} + 1.19\, M + 453\, e^{\text{[illegible]}} + 1.14\, B^{\text{[illegible]}} - 450)\,/B$$

where: M — miles
B — bps

The transmission cost/bit for five line lengths are shown in Figure 4, Bit Transmission Cost. Note that all curves have a minimum cost within the speed and mileage ranges. The cost/bit given by these curves is really the cost of sending a bit of information at a specific distance and speed for a month. Optimum speed is the real point of interest. The optimum speed is the one which has the minimum cost, or the derivative of the total cost curve with respect to the transmission speed is zero for a constant line length. These points (for each line length) are indicated by the arowheads.

In Figure 5, "Cost Effective Transmission Speed," presents the optimum speed for these line lengths between 100 and 3000 miles. Any deviation from this optimum will increase the cost. Returning to Figure 4, it can be seen that the curves are very flat around the minimum points. In fact, a variation in speed of $\pm$ 20 percent of the optimum speed increases the cost less than 5 percent. Once outside this range, the cost rises faster, especially for speeds lower than the cost effective speed.

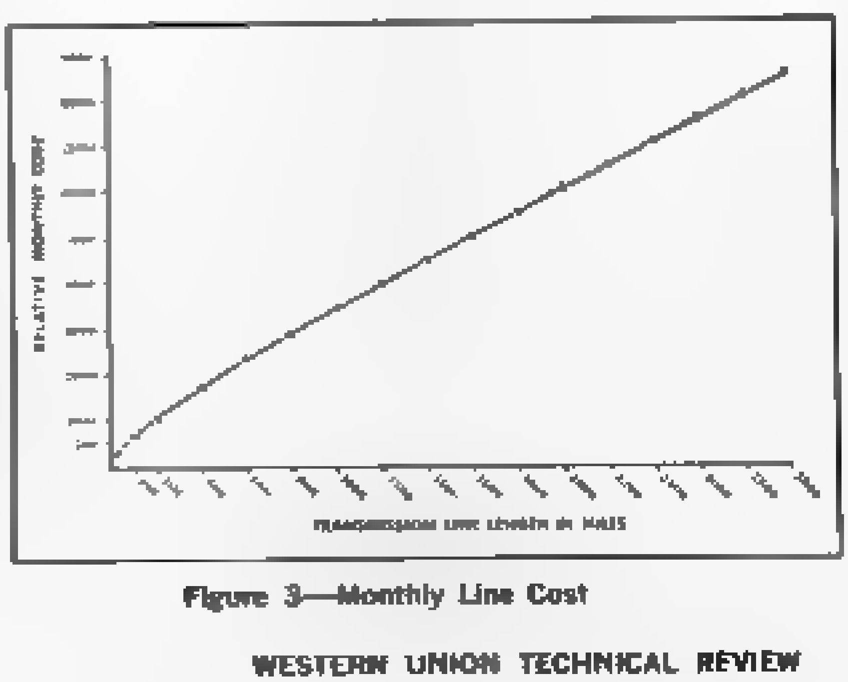


Figure 3—Monthly Line Cost

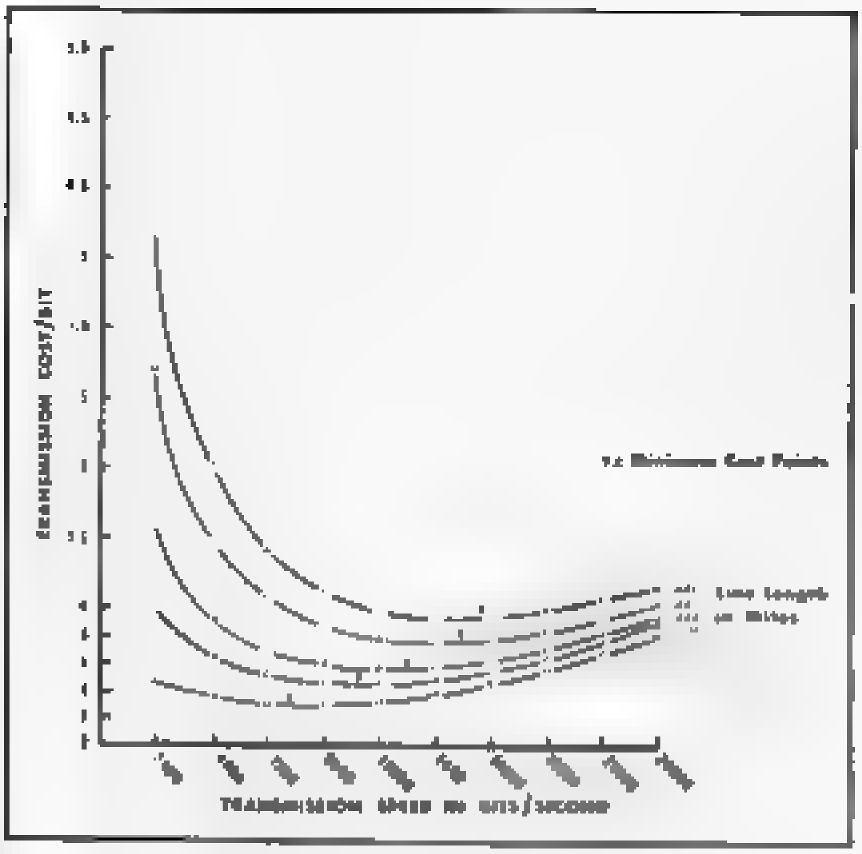


Figure 4—Transmission Cost per Bit

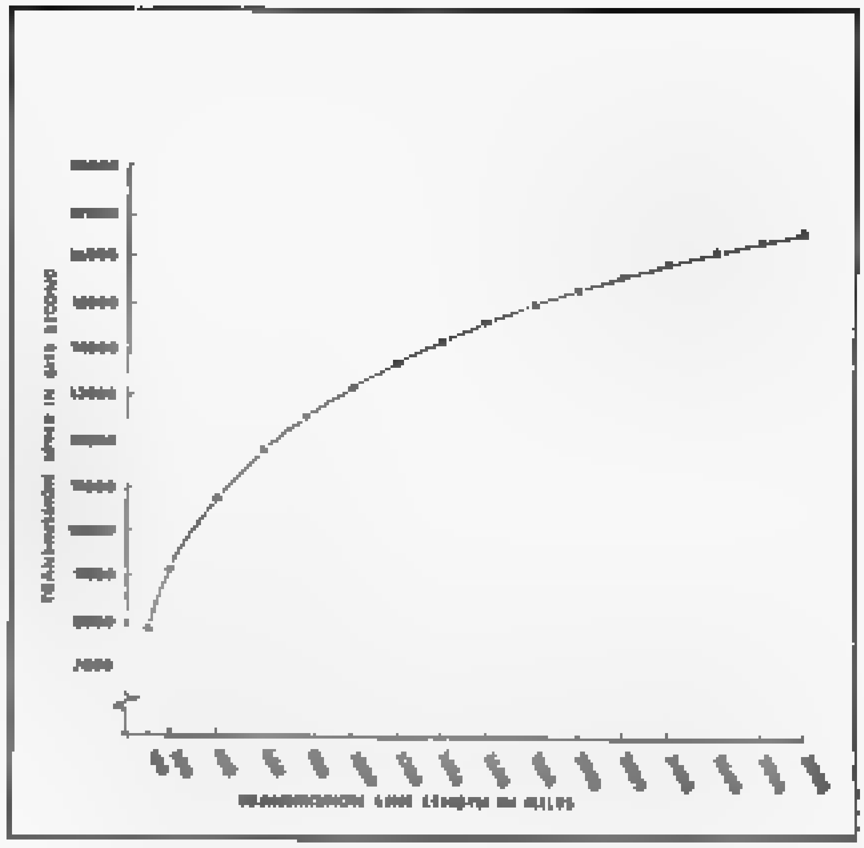


Figure 5—Optimum Cost Effective Speed

Cost Effective Speed

As indicated by Figure 5, the optimum speed ranges between 7900 bps and 16,700 bps as the circuit length increases from 100 to 3000 miles. Modems are not manufactured for all speeds but are designed in increments of 1200 or 1800 bps. The anticipated speeds are 2400-, 3600-, 4800-, 5400-, 7200-, and 9600 bps. Any circuit longer than 250 miles has an optimum speed greater than 9600 bps. It is not anticipated that modems operating faster than 9600 bps will be available in the near future if ever. The design problems are very complex, and the problems grow as the data rate reaches the "Implementation Limit."

The question then arises that, when limited to 9600 bps operation, is this speed cost effective? The answer is—Yes! For circuit lengths up to 1000 miles long, the increase in cost (compared to the optimum) is less than 6 percent. The longest circuit, 3000 miles, is 26 percent more expensive than its optimum. Table I shows the transmission cost for specific data rates relative

TABLE I

Relative Transmission Costs

Circuit Length	Relative Cost % Higher than Optimum				Optimum Rate
Miles	2400	4800	7200	9600	
100	42%	7.8	1	3.3	7900 BPS
1000	176	58	20	5.3	12900 BPS
3000	310	118	95	26	16700 BPS

to the optimum rate. It can be seen that an increase in the data rate provides a substantial reduction in cost. Operating at 9600 bps is cost effective compared to slower data rates, except for circuits shorter than 250 miles. The cost reductions that are possible for operating speeds greater than 9600 bps are much smaller than the reduction obtained as 9600 bps is approached.

The optimum speed is more sensitive to the circuit cost than the modem cost. There is a trend apparent which shows a consistent reduction in the rates governing circuit costs. Any reduction in these rates will also cause the optimum speed to decrease. It is also true that as the technology progresses, modem costs will also decrease. This will force the optimum rate to increase.

Conclusions

Cost effective analysis is a valuable management tool. It provides a quantitative measure of the cost and effectiveness factors pertinent to the system under analysis. It identifies the factors to be considered in the decision-making process and the values assigned to them. Also the interaction of the factors is defined. Thus, cost effective analysis augments decision-making with numerical reasoning, documented in a consistent and logical manner.

The cost effective data rate cannot be reached for voice circuit lengths longer than 1200 miles with an "Implementation Limit" of 13,800 bps. The highest data rate available is 9600 bps (70 percent of the "Implementation Limit"). Even if modems are available which operate faster than 9600 bps, no significant cost saving will be realized for circuits up to 1000 miles long.

For longer circuits, there is some advantage in operating faster. Considering the large reductions in cost/bit derived by operating at 9600 bps compared to slower rates, the decreases in cost/bit obtained by faster rates are small by comparison.

Most voice circuits in Western Union networks are less than 2000 miles long. The longest circuit, from Miami to Seattle, is 2723 airline miles. Therefore, most of the voice circuits will be operating within 20 percent of the optimum cost. Until higher speed modems become available, circuits longer than 1000 miles will have a cost/bit which ranges from 5 percent to 26 percent higher than the optimum. Higher data rates will reduce costs but large increases in the modem speed are required to produce significant results. Within present technology, the optimum rate will not be reached for circuits longer than 1200 miles. For circuits shorter than 1000 miles, a speed of 9600 bps is the most cost effective.

References

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2. The Mathematical Theory of Communication, [illegible] Shannon & W. Weaver, [illegible] Press, Urbana, [illegible] 964
3. Cost-Effectiveness Analysis as a Management Tool, [illegible] The Rand Corporation, October [illegible] 964, [illegible] 14

Acknowledgement

The author is indebted to M[illegible] R[illegible] [illegible] Manager of Network [illegible] who [illegible] the idea of this paper and guided its preparation.

The Author

[illegible] R. Aud[illegible] [illegible] Network [illegible] Engineering [illegible] networks [illegible] a four year tour of duty [illegible] service [illegible] development [illegible] evaluation [illegible] B.S. [illegible] Newark College of Engineering [illegible] graduate work [illegible]

Patents Recently Issued to Western Union

Patent No.	Title of Patent	Inventor
3 363 191	Data Transmission Amplifier	John E. Boughtwood Harold Harris
3 366 914	Solderless Connector for Printed Board Circuits	John J McManus Ralph Rosen
3,374,309	Duplex Way Station Selector	John Elich Vincent C. Kempf
3,381 370	Waveguide Flanging Method	Harry J Goonan J. K. Fitzpatrick
3,388 378	Error Detection and Correction Apparatus for Duplex Communication System	Robert Steeneck John R Cowan
3.391 386	Card Data Transmitter Circuit	Ronald J. Duswalt

Evolutionary Modernization of DCA's AUTODIN-CONUS

Western Union will modernize the domestic portion of AUTODIN, AUTODIN CONUS, under a $20 million contract from the Defense Communications Agency.

It plans to install new, advanced equipment which will double the transmission capability of AUTODIN. Presently, it transmits about a million words a day. The new equipment will make it possible to transmit two billion words a day.

The original system was designed by Western Union in 1963 for the United States Air Force. It now consists of nine major computer centers and can accommodate 2700 outstations.

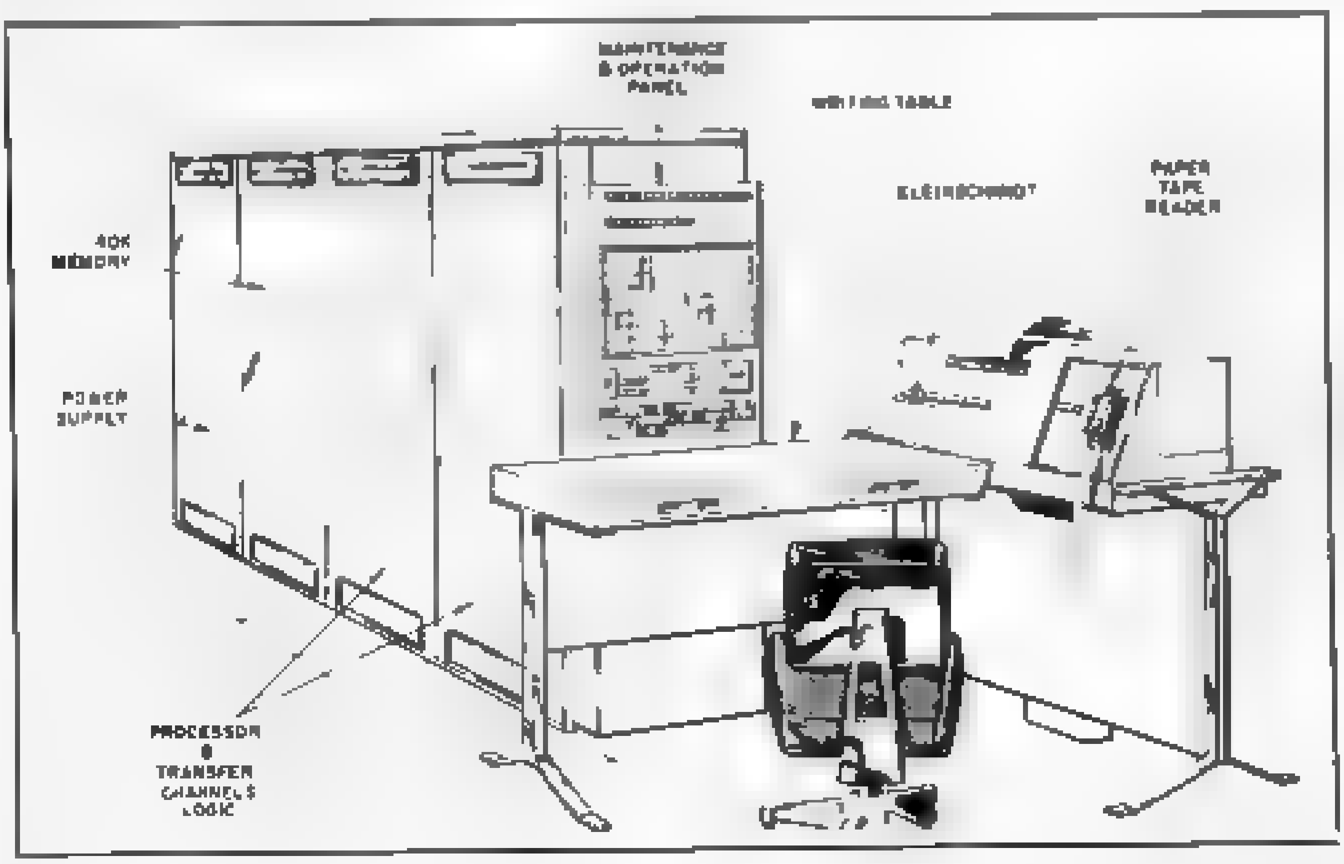
The new equipment will include 18 new, integrated circuit Communication Data Processors, new mass-memory units and 77 new, modern magnetic tape drives. All these will improve the system's reliability, reduce space, power and air-conditioning requirements. In addition, the overall operating efficiency will be enhanced.

This modernization also includes new automated techniques for failure diagnosis and integrated circuit module repair.

AUTODIN is presently the world's largest digital data system and provides high-speed interchange of vital communications for the entire defense establishment.

The Defense Communications Agency is responsible for and operates the global AUTODIN network for the Department of Defense.

Under the new modernization program Western Union will serve as the prime contractor to the Defense Communications Agency.



Artist Rendition of the Proposed New COMMUNICATION DATA PROCESSOR with low speed printer tape reader, operator's console and 4 racks of modules.

The System Console and Magnetic Tape Station at one of the Computer Centers taken with a 360° Lens.

ABSTRACTS OF ARTICLES IN THIS ISSUE

THESE ABSTRACT CARDS MAY BE CUT OUT AND PASTED ON LIBRARY CARDS FOR FILING.

Pulse Code Modulation
Cables
Test and Maintenance

Western Union TECHNICAL REVIEW, Vol. 22, No. 3 (Summer 1968)
pp. 82-93

This article reviews the development of Pulse Code Modulation and describes the first PCM installation at Western Union.

Western Union's cables between New York and Newark were used to evaluate its plant for digital operation and to test the available PCM equipment for reliability and performance. The impact of PCM operation on maintenance and operation personnel was also considered. The trial test proved that PCM equipment performed excellently on Western Union's cable plant and the operating and maintenance personnel were pleased with its reliability.

T1 Carrier
Pulse Code Modulation
D^4 Channels

Kostas, D. J. and van Gelder, R. B.: PCM—D^4 Channels

Western Union TECHNICAL REVIEW, Vol. 23, No. 3 (Summer 1968)
pp. 94-103

The T1 carrier system transmits 1,544,000 time slots per second. Time slots in the standard T1 terminal are allotted to twenty-four voice channels for digitally transmitting analog information.

Western Union modified the standard T1 terminal to provide D^4 channel transmission of 55 teleprinters in the T1 time slots allotted to only one of the 24 voice channels. This article describes the design of the 0-200 baud D^4 channel and suggests many applications of these channels.

Management Tool
Cost Effectiveness

Cost Effective Analysis
—Our Management Tool

Western Union TECHNICAL REVIEW, Vol. 22, No. 3 (Summer 1968)
pp. 110-114

Western Union has studied the cost of effectively using the voice band for data transmission. Two cost factors were used to determine the optimum transmission rate for a fixed length of circuit which will offer the lowest transmission cost.

The optimum rate varied from 7900 bps to 16,700 bps for circuits between 100 and 3000 miles long. The sensitivity of the optimum data rate shows total cost increases less than 5 percent when the optimum rate is varied ± 20 percent.

AUTODIN
Modernization
Announcement
AUTODIN-CONUS

Evolutionary Modernization of DCS's AUTODIN CONUS

Western Union TECHNICAL REVIEW, Vol. 22, No. 3 (Summer 1968)
pp. 116-117

Western Union has been awarded the contract to modernize the domestic portion of AUTODIN.

This article briefly describes the new equipment to be used and the automated techniques developed for failure diagnosis and integrated circuit repair.

Western Union

serves

National Political Conventions

Western Union is serving the 1968 national political conventions and transmitting press media all over the United States and abroad.

Four special press centers are being installed—two in Miami Beach and two in Chicago—for the Republican convention opening August 5 and two for the Democratic convention on August 26.

More than 200 operators, supervisors and technicians, specially trained in convention work, will be assigned to each city to handle the telegraphic press requirements of an estimated 5,000 news media representatives plus the communication needs of thousands of delegates and visitors. Staff assignments will be geared to meet peak-load requirements, world-wide time zones and newspaper deadlines.

Each convention facility will be served by more than 150 circuits with a capacity of more than 600,000 words an hour.

At Miami Beach 100 Telex machines will be installed in the Fontainebleau Hotel and at the convention site in the Memorial Auditorium.

At Chicago, similar staff and facilities will be located at the Conrad Hilton Hotel and at the convention site, the Internation Amphitheatre.

These Telex machines will permit direct connections to be dialed to subscriber newspapers, in seconds, for immediate, two-way communication and transmission of press copy.

Telex will provide foreign correspondents with immediate, direct communications, via the gateway facilities of the international telegraph carriers, to 150 overseas countries and territories ranging from Aden to Zambia.

Western Union will also install added equipment in its Miami Beach office to expand its message handling for the general public.

Personal Opinion Messages may be sent to representatives at these conventions.* ■

*The advertisement on the next page is one of several designed by the Marketing Department to describe the new Western Union services.